

Report No. CG-D-28-86

AD-A175 083

**ANALYSIS OF A STAND-ALONE POWER SYSTEM
FOR REMOTE-SITE APPLICATIONS**

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**FINAL REPORT
MAY 1986**

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Prepared for:

**U.S. Department Of Transportation
United States Coast Guard
Office of Research and Development
Washington, DC 20593**

Technical Report Documentation Page

1. Report No. CG-D-28-86		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle ANALYSIS OF A STAND-ALONE HYBRID POWER SYSTEM FOR REMOTE-SITE APPLICATIONS				5. Report Date May 1986	
				6. Performing Organization Code	
				8. Performing Organization Report No. CGR&DC 6/86	
7. Author(s) J. R. THACKER					
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center Avery Point Groton, Connecticut 06340-6096				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No.	
				13. Type of Report and Period Covered FINAL	
12. Sponsoring Agency Name and Address Department of Transportation U.S. Coast Guard Office of Research and Development Washington, D.C. 20593				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract The Coast Guard has over 40 automated remote lighthouses which are powered by a continuously run, diesel-electric generator. Continuous operation of a diesel generator increases maintenance requirements as well as fuel costs. Previous studies have indicated that maintenance and operational costs at remote, automated lighthouses could be substantially reduced by incorporating a hybrid energy management system. Such a 120-volt system was designed, developed, and built and includes the following major components: diesel-electric generator, wind turbine generator, battery storage, inverter, system controller and lighthouse load. This report discusses the system design, the chronological record of events, conclusions, and recommendations of over three months of continuous data collection and system operation. Additionally, each major system component is discussed in detail in an appropriate appendix.					
17. Key Words diesel generator charger wind generator efficiency inverter hybrid availability				18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) UNCLASSIFIED		20. SECURITY CLASSIF. (of this page) UNCLASSIFIED		21. No. of Pages	
				22. Price	

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

ACKNOWLEDGEMENTS

I would like to acknowledge with sincere appreciation the contributions of Lieutenant Albert Hartberger II, who supplied the material contained in Appendix B. Mr. Warren Heerlein contributed many of the system diagrams while EMI Eric Johnson supplied many of the schematics, for which I am deeply grateful.

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1.0 INTRODUCTION

1.1 Background

The United States Coast Guard presently operates over 40 lighthouses that are remotely sited where commercial power is not available. The present method for supplying the energy requirements of these lighthouses is to operate a 120 VAC diesel generator continuously. This continuous diesel operation keeps maintenance requirements high and consumes much fuel (Powell, et al., 1981). The Office of Research and Development at U.S. Coast Guard Headquarters, with the support of the Offices of Engineering and Navigation, initiated a four phase research program designed to investigate methods of reducing the total cost of remote lighthouse system operation and maintenance. These four phases are briefly discussed below.

Phase I

The first phase, completed in February 1981, consisted of a feasibility study focusing on remote site energy requirements and possible alternate energy solutions. This research was carried out by The Johns-Hopkins Applied Physics Laboratory (APL). The final report on this phase (POWELL, et al., 1981) favored a hybrid power system design incorporating an alternate energy source (wind) and a storage device (battery), as well as the standard automated lighthouse diesel-electric generator. Concerning the wind energy source, the report concluded that only the northern (e.g., remote stations located between 38°N and 48.4°N latitude) and Alaskan offshore sites were dramatically more economical than a simple diesel/battery cycle charge system. Additionally, they concluded that wind energy systems were more economical than solar energy systems everywhere except southern coastal sites. APL proposed two hybrid system designs, one of which was essentially adopted. The adopted system basically consisted of a diesel-electric generator, a 120 VDC battery charger, a 120 VDC wind generator, a 120 VDC battery bank, and a 120 VAC inverter to power the load.

Phase II

The purpose of the second research phase was to design, develop, and build an exploratory prototype to determine the basic suitability of the proposed hybrid energy design. APL initiated this work in the Fall of 1980. However, due to severe budget cutbacks, the program proceeded slowly through FY81, FY82, and FY83. The effort proceeded more rapidly in FY84. The prototype hybrid power system was assembled in the Spring of 1984 and underwent preliminary evaluation at Coast Guard Station Alexandria, Virginia. On 3 May 1984, the hybrid energy shelter containing the system components was installed at Cape Henry Light (LLNR 152), Virginia Beach, Virginia. During the summer months, the shelter was outfitted with the necessary power connections and data collection equipment. By late Summer 1984, APL had developed a microprocessor system for recording data within the hybrid system, assisted in initial building and testing of the hybrid system, and produced

visits and net fuel costs. Recognizing the benefits of extending the maintenance interval at such remote sites, an interim goal has been established (U.S. Coast Guard, 1985) at one visit per year. This is recognized as a formidable goal given that the average, Coast Guard-wide, maintenance interval for these diesel powered lighthouses is about nine weeks, as revealed by the FY85 ATONIS (Aids to Navigation Information System) data base. Therefore, a hybrid energy power system must be developed which will reliably power remote lighthouses (U.S. Coast Guard, 1981) and substantially reduce preventive and corrective maintenance visits, and fuel delivery visits.

1.4 Report Structure

This report discusses the data collected from 13 February to 16 May 1985. Section 2.0 describes the Energy Management Prototype Power System (EMPPS) including a description of the operating mode, a power flow diagram, system efficiencies and a discussion of the system design. A detailed description of each major component can be found in a dedicated appendix. Section 3.0 provides a revealing look at the chronology of the system. Included are the start and stop times for all charges and discharges, as well as discussions of significant aspects of the various charge/discharge cycles. Section 4.0 offers conclusions based on this effort and some related work. The supporting arguments for each conclusion can be found in the appropriate appendix. Section 5.0 provides recommendations for future efforts.

2.0 SYSTEM DESCRIPTION

2.1 Purpose

The purpose of this energy management power system is to provide economical and reliable power for our remote, unmanned lighthouses where commercial power is not available. A reliable stand-alone, hybrid energy system would reduce fuel costs (including personnel and fuel costs associated with delivery) and maintenance costs.

2.2 Operating Mode

As seen in Figure 2-1, the power system is conceptually simple. There are two power sources, the diesel-electric generator and the wind turbine generator. There is an energy storage device, the main battery bank, and an inverter to convert the direct current from the battery bank into alternating current. Finally, there is the aid-to-navigation load which draws energy from either the battery bank or directly from the diesel. After considering many operating philosophies, the final operating method selected is as follows. First, the battery bank supplies power to the load from full charge (100% state of charge, or SOC) down to about half charge (50% SOC). Second, when the 50% battery SOC is detected, the diesel generator comes on and simultaneously charges the battery bank and assumes the lighthouse load. This cycle is continuously repeated. Third, the wind generator always directs its energy into the battery bank regardless of the battery state of charge. There was no provision to dump excess wind energy into a dissipative load. Any excess energy was absorbed by the battery bank. The advantages to the above method of operation were two-fold: (1) by assuming the lighthouse load during battery charging, the diesel was more efficiently loaded, and (2) the battery is not loaded during recharge. This is desirable since most battery charging parameters are based upon temperature corrected voltages which are altered under loading.

2.3 System Schematic

Figure 2-2 gives a more detailed schematic of the energy management system. The major components of the system are delineated below:

- Diesel generator (Appendix A)
 - a. 24 V Nickel-Cadmium starting battery (Appendix D)
 - b. 24 V Edison battery charger (Appendix D)
- Main Storage Battery Charger (Appendix C)
- Main Storage Battery (Appendix E)
- Wind Turbine Generator (Appendix F)

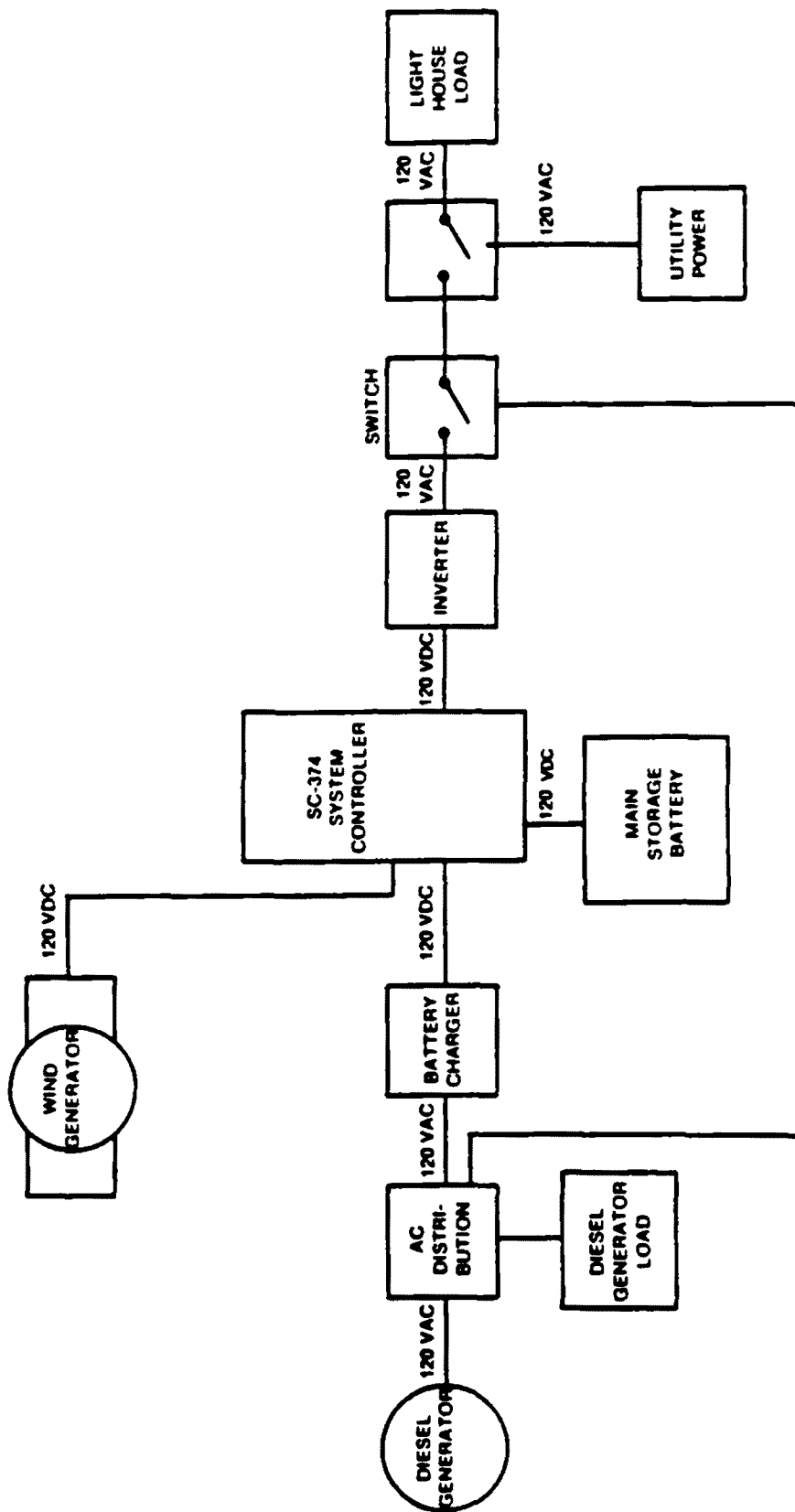


FIGURE 2-2 ENERGY MANAGEMENT PROTOTYPE POWER SYSTEM COMPONENTS

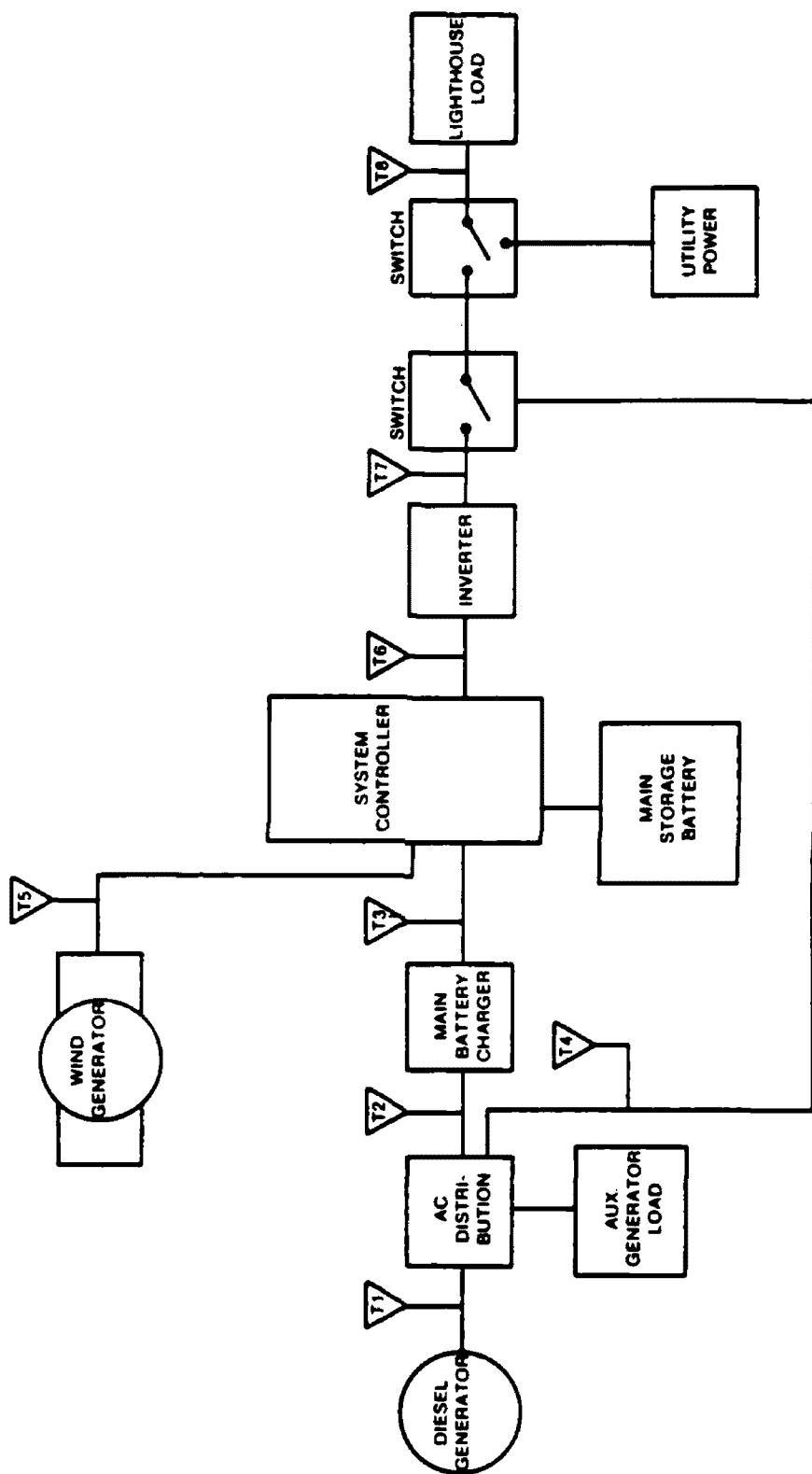


FIGURE 2-3 ENERGY DATA COLLECTION TEST POINTS

(2) The energy required by the lighthouse load (plus the 24 V charger) was only about 23% of the total diesel output. The remaining 77% of the diesel output went directly to the main battery charger.

2.5 Discussion of System Design

This was a trial system design. The present project plan calls for an advanced prototype design based on the experiences gained from this effort. As detailed in Section 3.0, this system had an operational availability of 71%. Although far short of the power availability expected from a local commercial utility (average availability greater than 99%), a first-trial hybrid power system operating satisfactorily 71% of the time is quite reasonable, if not laudable. However, operational requirements demand an improved design. More precisely, better performance is demanded of the six major components (Figure 2-1), which make up the basic system design. Although no availability data has been published on remote sites incorporating continuously operating diesel generators, the 1985 ATONIS data base reveals an overall average (from 44 sites) of about six discrepancies per year. If we assume ten hours of downtime for each discrepancy (60 hours for the year), this would yield an average availability of 99.3%.

As discussed in Appendix B, the DC-to-AC inverter was the primary source of system downtime. As a vital link, the unsuitability of the inverter for this application resulted in frequent system failure. The inverter reliability problems combined with an average efficiency of about 72%, indicate that any advanced system should NOT incorporate a single inverter (if an inverter must be used) to carry all lighthouse loads.

As indicated in Appendix F, the wind generator experienced two failures during the course of this experiment. In both cases, the reverse current diode (RCD), which prevents the battery from discharging into the wind generator, failed. Unfortunately, the source of these failures could not be determined from either the collected data or on-site inspections. Since the inverter was found inoperative each time the wind generator's RCDs failed, it is strongly suspected that large voltage spikes associated with the failure of the inverter to be the source of the wind generator problems. The replacement of the RCD is a relative simple operation. As pointed out in Appendix F, redundant RCDs could prove useful in extending the wind machine's reliability. In any event, the two RCD failures required two nonscheduled maintenance visits within a single 90-day period. This is unacceptable as discussed in Section 1.3.

Significantly, this experiment demonstrated that automatic starting and stopping of diesel-electric generators at remote sites is completely reliable (Appendix A). The diesel always started when required and there were no starter motor failures. This result is significant because we now know that we do NOT have to require continuous diesel operation just for the sake of reliability. In particular, excess diesel energy from relatively short operational periods (six to eight hours) can be stored in a secondary battery

3.0 CAPE HENRY CHARGE/DISCHARGE CHRONOLOGY

During the course of this experiment, which ran for about 2175 hours, the charge/discharge cycles varied considerably. Figure 3-1 is a time-line presentation of the charge/discharge cycling that occurred at the test site. Based on collected data, 23 charge/discharge cycles were completed between 14 February and 15 May 1985 (91 days). The large swings in cycle charge and discharge times is striking. Of course, the cycling regime is tied to the flow of charge into and out of the battery bank as sensed by the North Wind controller (refer to Appendix G). Most wind energy was input during the discharge cycles due to the ready charge acceptance and low voltage conditions of the battery bank. Therefore, the length of the discharge cycle is proportional to the wind availability and not constant. However, since very little wind energy was input to the batteries during the charge cycles, the charge cycle length ought to be relatively constant assuming battery, charge controller, and charger all perform in a constant manner. For the first 10 cycles, the charge time remains reasonably near the average of about 20 hours. It is interesting to note that although there is considerable difference in charge times, the variation in the amount of energy in ampere-hours (Ah) put into the battery bank during the different charges is reasonably small as shown in Figure 3-2. This phenomenon explains the variation in system inefficiency since the diesel runs longer in one case but the result felt by the batteries is basically the same. This is illustrated in Figure 3-1 by charge cycles 6 and 11. Charge cycle 6 output about 222 Ah during a 21-hour charge period while charge cycle 11 output about 219 Ah during a 45-hour charge period. The ordinate values in Figure 3-2 are the ampere-hours sensed by a watt-transducer in line with the battery bank and therefore take into account any load conditions present on the battery. During most of this experiment, the inverter (Appendix B) was always on, even during the charge cycle, representing a constant load of about 60 watts. Unfortunately, at the end of a charge period, the charger output was about 3 Amperes (A) but the inverter was drawing about 1 A creating a net effect of charging the battery bank at about 2 A. This created a totally unacceptable condition wherein the diesel would run in an extremely lightly loaded condition, only pushing 2 A per hour into the batteries. Meanwhile, the North Wind controller was counting the Ah input waiting to finally reach the 95% cutoff to shut down the diesel. This is what occurred at cycle number 16, Figure 3-1, where the diesel finally shut down after about 270 hours of inefficient output. The previous cycle, number 15, demonstrated similar tendencies but the diesel ran out of fuel after about 80 charge-hours, ending the charge. Why this phenomenon did not occur at every cycle (especially the first 10 cycles) is unknown. It is also interesting to note that the charger output varied with ambient temperature as illustrated in Figure 3-3. The equation of the least-squares fitted line is:

$$Ah = 86.3 + 1.56 T$$

Starting with about cycle number 20, a relay was installed in the system which would shut the inverter off during charging. The consequent reduced charge times can be seen in Figure 3-1.

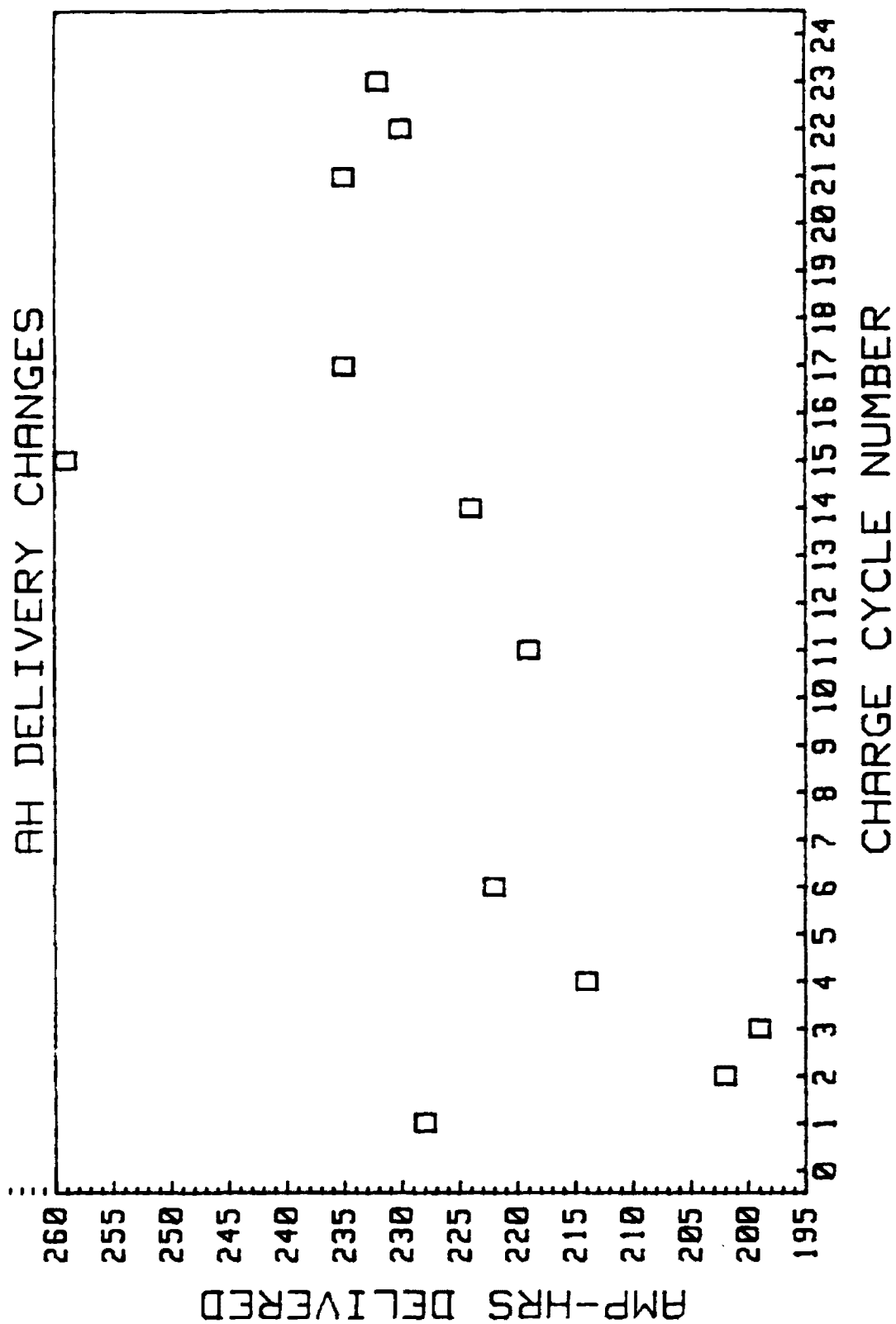


FIGURE 3-2 VARIATION OF CHARGE INPUT OVER VARIOUS CHARGE CYCLES

Table 3-1 indicates the actual time periods during which the system was inoperative including the time required to respond to the failure. The operational availability for this system was 71%.

TABLE 3-1

<u>DATE/TIME SYSTEM UNAVAILABLE</u>	<u>HOURS</u>
1400, 24 March - 0800, 08 April	354
0622, 22 April - 1540, 30 April	201
0906, 06 May - 1740, 09 May	<u>80</u>
Total Hours	635

The cyclic chronology is discussed in detail below to bring to light some of the test results.

Cycles 1 - 9: These are considered "normal" cycles with little exceptional points of interest. Representative plots can be found in Appendix M.

Cycle 10: Here, the discharge cycle is interesting since it reveals the effectiveness of the wind source. Figure 3-4 indicates how the battery state of charge varied with time during the 10th discharge. The solid line is the predicted SOC function assuming no wind energy input. Figure 3-5 depicts the wind energy input (sampled every 20 minutes) during this discharge period. Due to the wind input, the state of charge increases from about 61% to about 79% with a corresponding bank voltage increase from 116 VDC to 134 VDC. The wind input of about 389 Ah increased the discharge time by almost 36 hours.

Cycle 11: Figure 3-6 illustrates the battery current flow during the 11th charge/discharge cycle. The negative ordinate values indicate net current put into the battery during charge while the positive ordinate values reflect the net current drawn from the batteries during discharge. The net integrated energy input during charge was 219 Ah. However, the integrated charger output was about 315 Ah. Therefore, during the course of the charge, about 30% of the energy output by the charger was used to supply loads demanding from the battery bank (an average load of about 2 A). The cause of the lengthy charge time (approximately 45 hours) is due to the low net current input to the battery bank at the end of the charge. This is due primarily to the presence of DC loads on the battery bank during charging. This battery charger wasn't designed to handle the presence of a DC load during charging since it depresses bank voltage and alters the true taper set point.

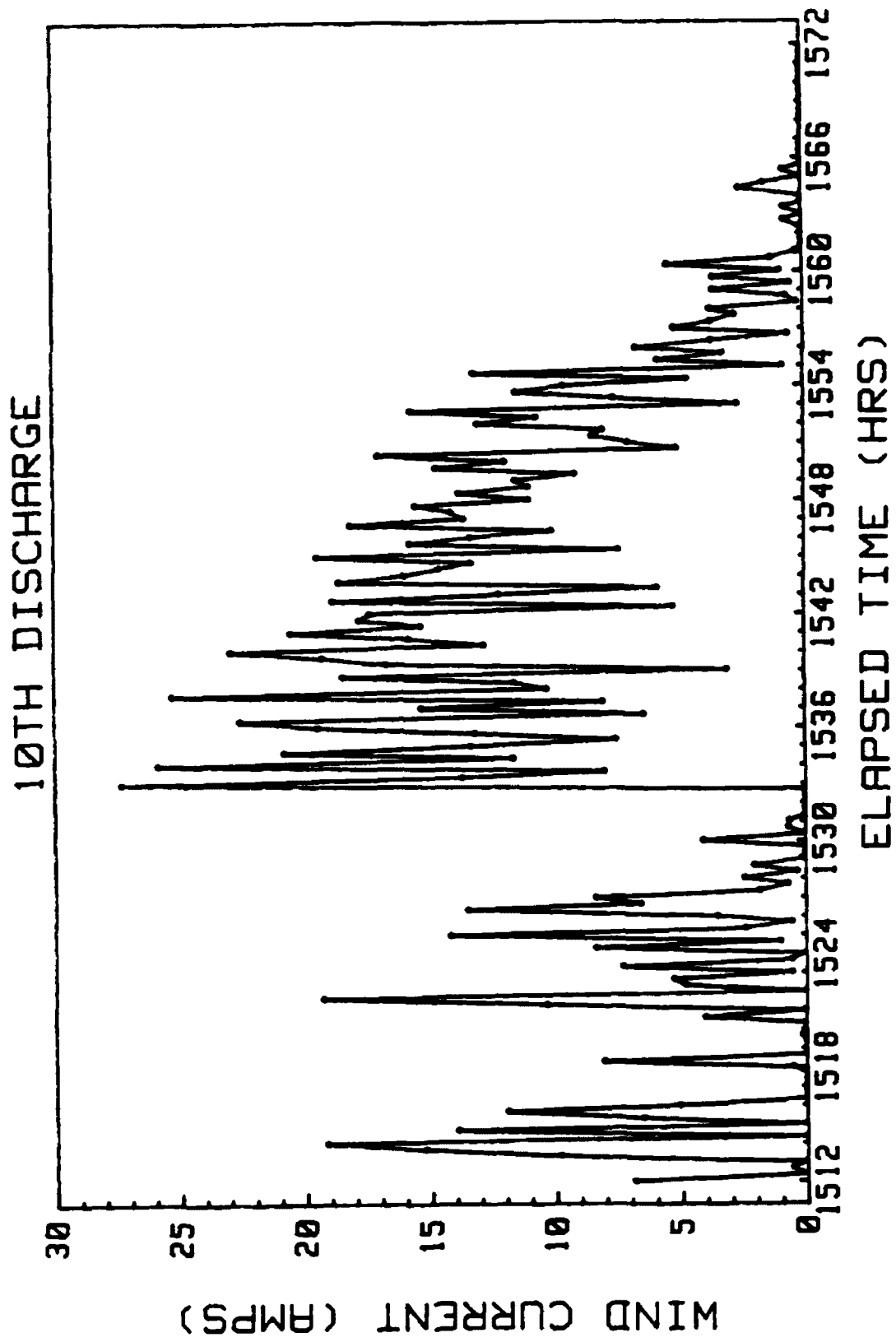


FIGURE 3-5 WIND ENERGY INPUT OVER THE DISCHARGE CYCLE

Cycle 15: Figure 3-7 describes the net current into the battery bank during the 15th charge cycle. Again, note the long tail at the end of the charge. The net total energy input during the charge (provided by the charger) was 292 Ah. The charge cycle finally stopped after 80 hours when the diesel generator ran out of fuel. After the charge process halted, the discharge immediately commenced. Figure 3-8 depicts the change in battery state of charge as the discharge proceeds. The rises in SOC are due to wind energy input. Note that due to the wind energy input, the discharge was lengthened by about 65 hours. Since the diesel was unable to come on, the system was forced to discharge until load disconnect. What follows is an interesting scenario based on data collected every 20 minutes. The North Wind controller is designed to disconnect the lighthouse load when the battery SOC has dropped below a preset SOC, in this case, 45%. This feature is designed to protect the battery from overdischarge. At about 11:00 a.m., 24 March, the load was finally disconnected due to low SOC readings. The inverter, which draws power from the battery even in the standby mode, was still drawing from the battery. At about 11:20, the data indicate the lighthouse load had been reassumed and the light was on. But at 11:40, twenty minutes later, the load had been disconnected and remained so until about 5:00 p.m. when, again, the load was picked up, carried for less than two hours, then disconnected for the last time. Interestingly, the inverter failed at about 12:20 p.m., but was operating at 12:40. The inverter then failed again at 1:00 p.m. and remained off until 4:00 p.m. At about 4:20 p.m., the inverter failed again and remained off until 5:00 p.m. The inverter finally failed for the last time at 6:40 p.m. The reason for this on/off cycling is that the "c" relay in the North Wind controller (see Appendix G) was chattering. The hysteresis on the relay is only about 1% to 2% and this change in SOC is easily exceeded by gusting wind. The result is shedding of load, followed by a large wind burst with attendant increase in SOC which causes the load to be reassumed. The discharge process resumes and so again the battery is dragged down and the load is disconnected. As long as the wind is available, the potential for this cycling is there. In this particular case, the inverter finally failed and the lighthouse load was picked up by commercial source until repairs could be made. Note that after the commercial source assumed the load, the batteries were charged to about 58% SOC by the wind generator. The inverter was discovered to have a failed diode the failure of which, according to the manufacturer, is usually caused by spikes on the DC input.

Cycle 16 - This cycle convinced us that the inverter must be turned completely off during the charge cycle. Its "standby" power consumed was about 60 watts. However, as a DC load, it lowers the battery voltage and affects the output of the charger as seen in Figure C-3 (Appendix C) where cycle number 22 (with inverter shut-off) performs much better than cycle number 3.

Cycles 21-23 - These cycles represent basically the "fine-tuned" version of the system. Here we see shorter charge times, about 14 hours, with more energy input, approximately 232 Ah. The discharges are routine, on the order of 24 hours.

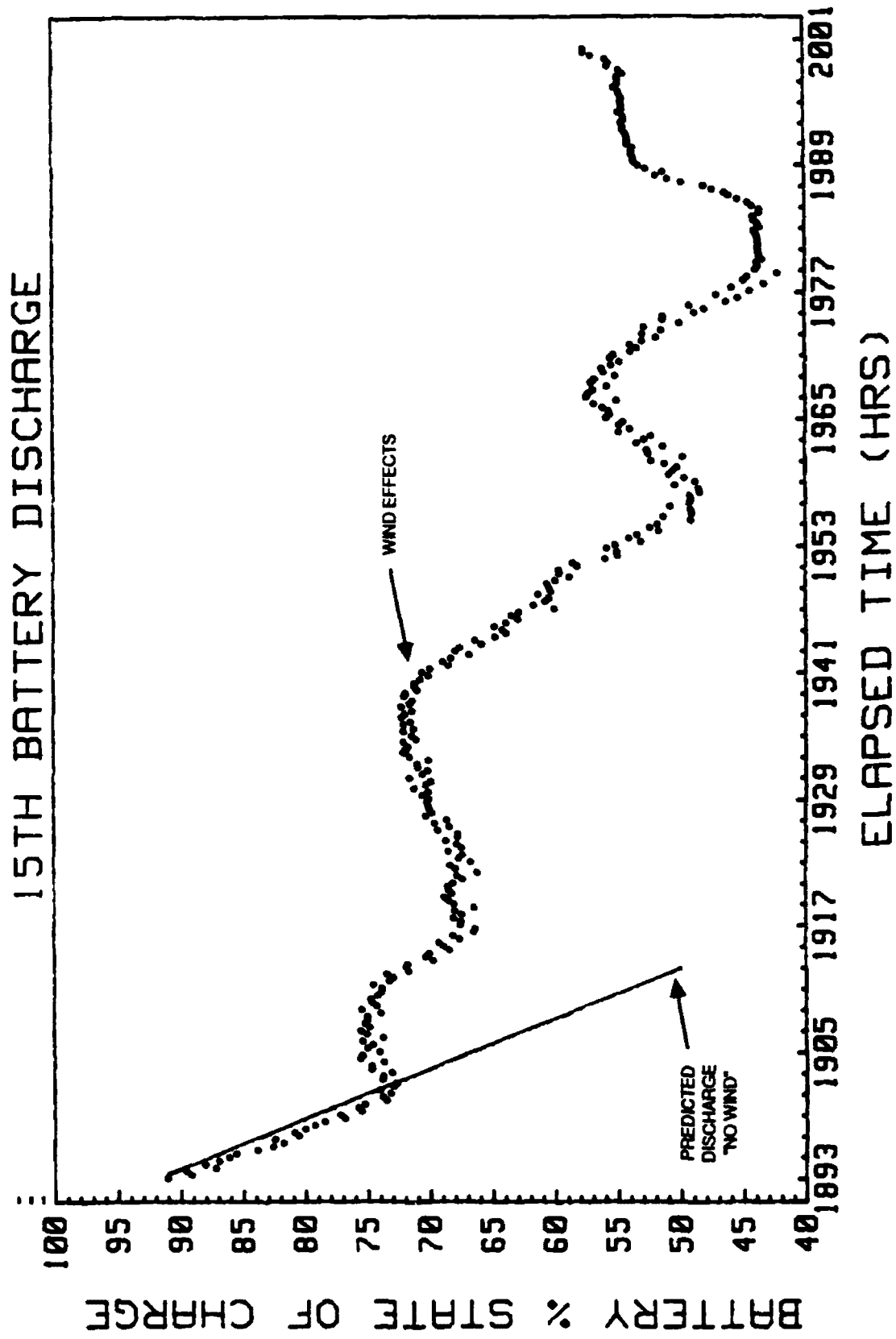


FIGURE 3-8 BATTERY SOC OVER A DISCHARGE PERIOD

4.0 CONCLUSIONS

The conclusions from our energy management prototype experiment at Cape Henry, Virginia are given below. The portion of the text which specifically deals with that issue is also given.

- (1) This system was operationally available 71% of the time (Section 3, page 3-5). Although not meeting the desired field deployable availability of greater than 99%, the availability obtained was quite reasonable if not laudable for an initial trial system. System reliability is of paramount importance in this application, and our experience indicates that diesels can be automatically started and stopped reliably (Appendix A, page A-2). This removes a major area of reliability concern. A key component in this system is the main storage battery. To attain high reliability, long life and cost effectiveness, these batteries must be maintained properly (Appendix E, page E-5). Specifically, the appropriate battery technology must be determined for site conditions, the batteries must be correctly sized, they should be thermally managed, and provisions should be made to deal with the electrolyte stratification problem. The fire suppression system was adequate and should be employed in future systems. Also, an environmental control unit may be required in future systems.
- (2) The present design experienced some problems. The inverter was unreliable and played a significant role in system downtime (Appendix B, page B-6). In this design, a single inverter was employed to handle all AC lighthouse loads. This is not a good design for two reasons. First, if the inverter fails, the entire system fails; second, use of a single inverter which must meet all peak load requirements is inherently inefficient. In our case the average efficiency was about 72%, implying that 28% of the energy drawn from the storage battery was wasted. A new design should employ several inverters, each dedicated to specific lighthouse loads. This will increase efficiency and reliability. If an inverter fails, at least the remainder of the system would remain operational. A new design might consider Direct Current operation, eliminating the inverter requirement altogether. However, due to the large battery bank voltage range (115 VDC to 150 VDC for 60 cells) dedicated DC-to-DC converters may have to be employed. The wind generator experienced two failures during the test period (Appendix F, page F-3). Neither failure was serious from a hardware point of view, but both required a nonscheduled maintenance visit which strikes at the heart of the reliability economics issue. It appears that some minor design changes (namely, redundant reverse current diodes) could alleviate the problem. More operational data for this machine, as well as others in this power range, is required in order to assess the general suitability of wind generators for this application. In this particular system, the diesel was inappropriately sized, resulting in

5.0 RECOMMENDATIONS

Based on the information that has come to light since the Energy Management Prototype Power System was installed in 1984 at Cape Henry, Virginia, the following are recommended:

- (1) Work should continue on the advanced prototype design incorporating the lessons learned from the present design. As the final iteration, this advanced prototype should be rigorously tested and evaluated to determine its usefulness for this application. The advanced prototype should employ either direct current or else dedicated, reliable inverters. A different battery should be employed in the advanced prototype, in particular, one which is capable of dealing with the thermal management, automatic equalization, and stratification issues as discussed in Appendix E. The conventional main battery charger presently employed should be replaced with a programmable microprocessor based charger. Due to intermittent loads and unpredictable surges in wind energy input, the battery bank voltage will fluctuate (typically 2 to 3 volts). Therefore, where possible, control devices should NOT be voltage triggered unless adequate provision has been made to deal with random voltage fluctuation. The present mechanical system controller should not be carried over to the new design but should be replaced by a microprocessor based controller. The present wind generator should be carried over to the new design, but should employ redundant reverse current diodes.
- (2) Since the main storage battery is a key component, battery research should be conducted to examine appropriate, available technologies including lead-acid, Nickel-Cadmium and gel cells for this application. The charge regime is crucial and must be based on charge acceptance and independent of battery age, operating temperature and state of charge. Before employing any battery for this application, it must be properly sized for the particular installation and have a system-based mechanism for dealing with thermal management, water loss, electrolyte stratification, and equalization of cells.

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APPENDIX A DIESEL ELECTRIC GENERATOR

Purpose

This engine generator set was incorporated in the energy management power system to:

- (1) provide power to the battery charger, and
- (2) provide power to the lighthouse load during battery charging.

Description (refer to maintenance manual)

The engine generator set is a standard, class 2, high endurance set which is standard equipment at most remote lighthouses employing automation equipment. The engine used is a Lister model SR-3A. This engine is a naturally aspirated, air cooled, four cycle, inline cylinder type, modified for dry sump lubrication. The engine is rated at 18 BHP, has a compression ratio of 18.5:1, and rotates counter-clockwise when viewed from the flywheel end. The engine can be started electrically (24 VDC) between 100°F and 125°F, or hand cranked above 32°F. An external oil tank has been provided in the skid base to supply a modified 40 gallon dry sump operation.

The 325-pound generator is a single bearing type and manufactured by Lima Corporation. The generator is rated at 10 kW (12.5 kVA), 60 Hz, and 120 VAC, single phase output. The generator is also capable of three phase operation in either Wye or Delta configuration. This is a brushless, four pole, externally regulated, rotating exciter type generator consisting of a conventional stator, salient pole revolving field system coaxial with the field and rotating silicon rectifier assembly. An external voltage regulation system supplies the main excitation to the generator.

Performance

During the period 13 February to 16 May 1985, the diesel generator accumulated about 1075 operating hours. One diesel failure occurred during this period. At about 5:00 p.m. on 2 May 1985, the diesel AC output, 150 A, circuit breaker tripped. The diesel generator continued to run but produced no electrical power due to the tripped breaker. Investigators reset the breaker at about 2:30 p.m., 3 May, and after checking other system components and detecting no obvious failures, departed the site. At approximately 3:00 p.m., 3 May, the diesel circuit breaker tripped off again and remained off until repaired on 6 May. Additionally, the wind generator's reverse current diode failed some time between 2:25 p.m. and 2:45 p.m. on 3 May. The cause of the diesel circuit breaker tripping during the above period is unknown. However, a similar failure occurred again in September 1985. At that time, it was noted that one of the breaker input cables had vibrated loose causing intermittent connection with attendant arcing. Apparently, this cable had been solder tinned before being placed in the breaker. As a result, when the set screw was tightened, the tinning wouldn't allow the connection to pressure conform.

0.45 g/hr. and for cycles 18 through 23, the consumption rate averaged 0.55 g/hr. The last cycle group is more efficient because during this period, the inverter was shut off except when actually providing power to the load. Figure A-1 is a plot of fuel consumption rate for a standard SR-3 LAMP high endurance engine generator. This plot is taken from fuel consumption rates obtained from Lister Service Bulletin 268 of August 1980. Fuel consumption rates for 30% and 40% of full load are extrapolated from Lister data and represent estimates. As indicated in Figure A-1, the diesel was only operating, on average, at about 30% of its maximum capability for the first 17 charge/discharge cycles. During the final group of cycles, the diesel averaged about 40% capacity operation. The desired loading for these diesel electric generators is greater than 75% (para 3-D-4a, Coast Guard Automation Technical Guidelines). Extended operation below this level leads to premature carbon buildup which can cause damage to valves, rings and valve guide seals. Based on fuel consumption rates for this particular installation with its relatively small load (less than 2 kW), the SR-3 is too large.

APPENDIX B INVERTER

Purpose

The inverter was used in the energy management prototype power system to convert battery bank 120 VDC to 120 VAC at 60 Hz to power lighthouse and power system loads. These loads included a nominal 1000 watt flashing light (50% duty cycle), a 160 watt fluorescent light fixture, a 24 V battery charger, the power system environmental control unit and other miscellaneous loads. The total average load was about 1400 watts.

Description

The inverter used in the prototype power system was manufactured by Best Energy Systems for Tomorrow, Inc. as model M120-6000. This inverter has no moving parts requiring only battery input voltage to operate. The output frequency of the inverter is crystal controlled and its modular design facilitates on-site diagnosis and repair. The following characteristics are pertinent.

MAX Load (10 min.).....	6000 watts
MAX Continuous each leg.....	2500 watts
MAX continuous total.....	5000 watts
MAX surge load.....	24,000 watts
Nominal input voltage.....	120 VDC
Input range.....	110-140 VDC
MAX output 120 V/240 V.....	50/25 Amperes
Efficiency.....	90% full load
No load current.....	2.3 Amperes
MAX inductive motor.....	3 hp
MAX universal motor.....	7 Hhp
Height.....	21 1/4 in.
Width.....	22 1/2 in.
Depth.....	9 1/2 in.
Weight.....	160 lbs.
Voltage regulation.....	+/- 5% no load to max load
Frequency output.....	60 Hz (+/- 0.002)
Power factor.....	1 to 0.7
Low AC output.....	96 VAC
Temperature range.....	-20.0 to 100°F

Installation

The Best inverter is small enough to be used in almost any application. Battery input to the inverter should be connected with "quick disconnect" couplings and the positive voltage lead should have a 150-Amp fuse. The fuse should be as close as possible to the positive battery terminal. The inverter can be wall or floor mounted.

Output (AC) wiring for the M120-6000 inverter should be number 6-AWG. The

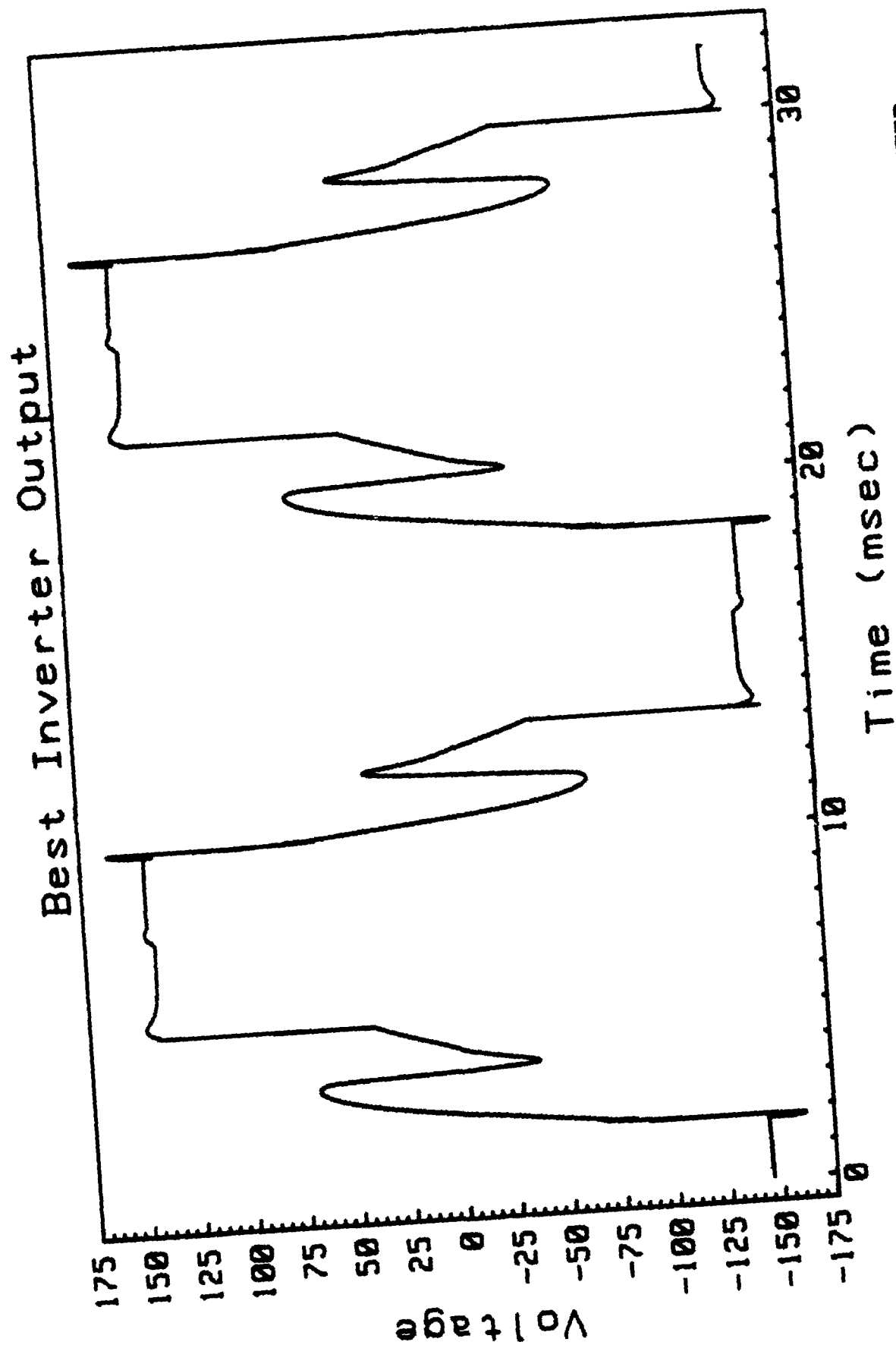


FIGURE B-1 NORMAL (NO LOAD) OUTPUT WAVEFORM FOR BEST POWER INVERTER

Best advised, based upon a field evaluation of the system, that there was no obvious problems which would have caused the failure. The silicon controlled rectifier (SCR) diode failure noted here was the most common failure throughout this test program. Printed circuit board number 2 was repaired and part RR93 was replaced.

25 April 1985

The Best representative was tasked to troubleshoot and repair the failed inverter, as well as to analyze the cause of the recurring inverter problems. A written analysis of the cause of the recurring failures has not been received to date.

30 April to 1 May 1985

The 30-Amp circuit breaker on the system controller kept tripping. This breaker was in series with the 60 A breaker on the inverter input. No abnormal conditions were found. The system controller circuit breaker was removed. The inverter was again suspected of contributing to component failure.

6-10 May 1985

The inverter SCR's failed when the inverter was powered up while the diesel generator was operating. Two switching diodes (SCR) had to be replaced. Duplicate replacement parts could not be obtained locally even at high-technology electronics shops. The original parts were rated 800 V, 200 A. The replacement parts, locally procured were rated 1000 V, 400 A. Best, Inc., suggested the power factor (PF) circuit be disconnected. The PF circuit can cause switching diode failure if it tries to compensate for non-existent inductive loads. It should be noted that the prototype power system at Cape Henry pushed the inverter to its specifications limits in many areas.

13 February 1986

Coast Guard Research and Development Center personnel did a complete bench test of the inverter since its last failure on 15 May 1985. The inverter was repaired with the following action:

Replaced R8 and R9; These resistors are 2000 ohm, 20 watt each, connected in parallel. During operation, they became hot enough to melt the insulation off of nearby wires. They were replaced with one 1000 ohm, 100 watt, chassis mounted unit.

Replaced SCR1 and SCR2; Both switching SCRs were shorted.

Replaced D7; This full wave bridge was shorted.

Replaced SCR3; This SCR was failed open.

APPENDIX C MAIN BATTERY CHARGER

Purpose

A model A-45, LaMarche battery charger was installed in the system to charge the main storage battery. This 120 VDC charger, manufactured by LaMarche Mfg. Co. (106 Bradrock Drive, Des Plaines, Illinois, 60018), is of the magnetic amplifier (mag-amp) variety and was designed nearly 20 years ago for the industrial (traction) truck industry. The 120 VAC required input to the charger was provided by the diesel generator.

Theory of Operation

The operation of this charger depends on a saturable reactor (labelled "SR" in Figure C-1). When attached to a discharged battery, the current flows into the battery (which has a high charge acceptance and will therefore accept high charge currents), causing the reactor to saturate and output maximum current. As the battery charges, its voltage rises, causing a corresponding decrease in charger current and saturation which results in a decrease in the charge rate. In this system the charger's output at the end of the charge was about 3 A to 4 A. The amount of time the charger was on was dependent on the controller's state of charge meter. At the beginning of the experiment, for example, the inverter would remain "on", (although not supplying power to the load) even during the charge process. At the end of the charge, as the battery was approaching 95% SOC, the charger's output had dropped to about 3.5 A. Due to the draw by the inverter, the charger was effectively charging at less than 1.0 Ampere and the controller would keep the charger (and diesel) operating until 95% SOC was reached. There were some long charge times until a relay was inserted to turn off the inverter completely when its output was not required.

Specifications

- Input: 120 VAC, single phase, 60 Hz
- Output: nominal 120 VDC; 32 A maximum current
- Automatic AC line compensation
- Automatic overload protection (current limiting)
- Automatic DC voltage regulation
- Hermetically sealed silicone diode full-wave rectifiers
- Automatic surge protectors
- No moving parts except clock (which we did not employ)
- DC ammeter
- Fused AC input and fused DC output

Performance

This charger operated without failure throughout the test period and is considered extremely reliable. However, it was noted that the last five charge cycles seemed to input more energy into the battery in less time than

previous charges. There is an adjustable resistor designed to alter the finish charge rate but it wasn't altered. It's possible that excessive heating or age could have affected the internal components; however, the likely cause of this variation can be attributed to aging and temperature effects on the battery bank voltage. The charger's output varies with the bank voltage sensed. Figure C-2 is a plot of the typical charger input with time and charger output with time. A ratio of kilowatt-hours output to kilowatt-hours input yields a charger efficiency of 82%. Figure C-3 illustrates how charger output varied over the course of the experiment.

Suitability

This charger, dependable and virtually maintenance free, is well suited for the traction industry for which it was designed. It is NOT suitable for this application, however (Thacker; 1985). This particular charge regime returns charge at such a low finish rate that the electrolyte becomes severely stratified resulting in eventual loss of battery capacity.

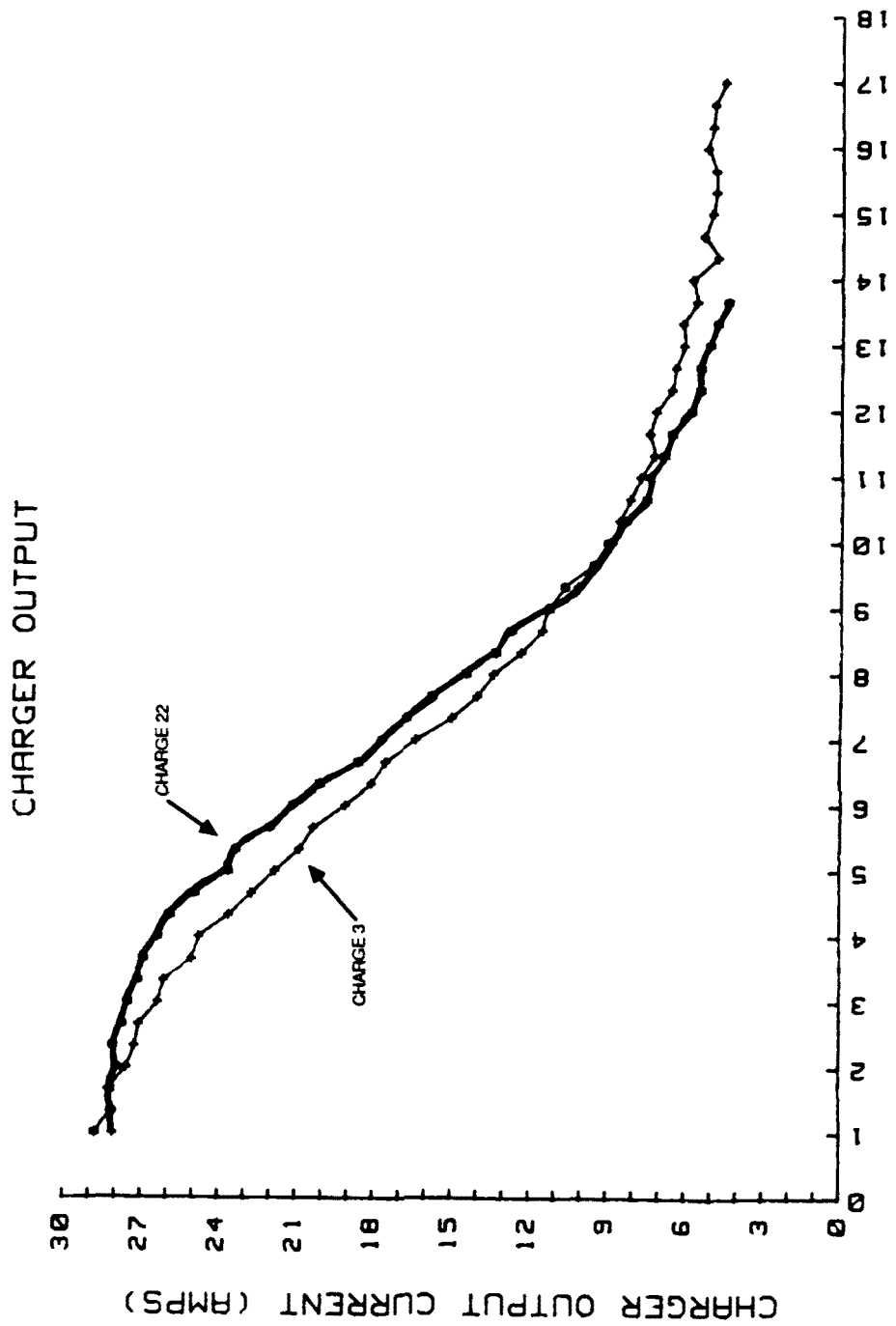


FIGURE C-3 CHARGER OUTPUT

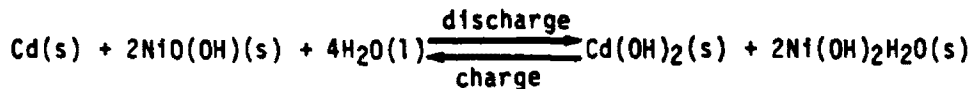
APPENDIX D STARTING BATTERY AND CHARGER

Purpose

When the battery state of charge reaches about 50%, the diesel is designed to come on to charge the main energy storage battery and assume the lighthouse load. The energy required to start the diesel generator is provided by a nominal 24 V, 20 cell, Nickel-Cadmium battery, model HED-100, manufactured by McGraw-Edison (Edison Division of McGraw-Edison, P.O. Box 28, Bloomfield, New Jersey 07003). A 24 V battery charger is required to charge the Nicad starting battery. The charger installed in this system, model CDSA-IBC 24-20A, is also manufactured by Edison (Edison Battery Division of McGraw-Edison, 6410 West Ridge Road, Erie, PA 16506). This charger runs off the diesel whenever the diesel operates.

Nickel-Cadmium Battery

The Nicad battery is a secondary, alkaline pocket plate storage battery using an aqueous potassium hydroxide electrolyte. These cells were chosen for this application because they are characterized by long cycle life, ability to charge and discharge at high rates, continuous overcharge capability, low maintenance, reliability, ability to operate at low temperatures and nearly constant discharge voltage. The basic overall cell reaction is given by (Vincent, 1984):



In these pocket plate batteries, the active materials may be found in specially designed perforated nickel-plated steel pockets. This design means that additives (typically graphite) are required to transfer the current to the steel plates. Over time, the graphite oxidizes and potassium carbonate builds up in the electrolyte reducing conductivity, increasing cell internal resistance. This problem is solved by changing out the electrolyte every 10 to 15 years. Some important points to remember about Nicad:

- (1) The electrochemical potential for this reaction is nominally 1.3 V per cell.
- (2) The electrolyte specific gravity does not participate in the main cell reaction, and so is virtually independent of battery SOC; consequently, the freezing point and internal resistance are not affected by SOC.
- (3) The state of charge of Nicad cells is not easily determined.
- (4) These cells should not be operated above 45°C.
- (5) With both lead-acid and Nicad cells in the same enclosure (the energy management plastidome), all personnel must be warned not to use the same hydrometer for both lead-acid and the alkaline Nicad.

24 VDC BATTERY CHARGER

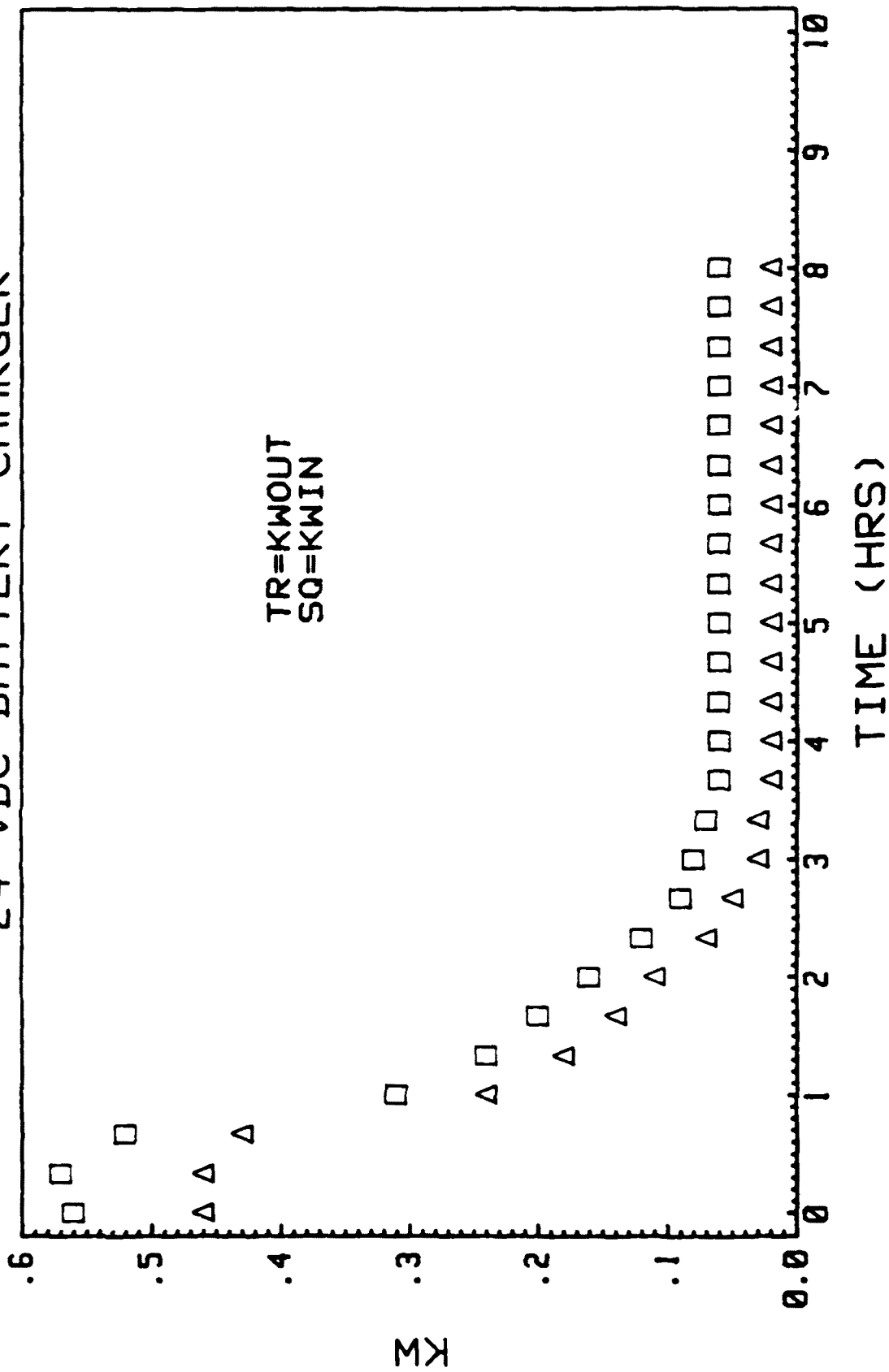


FIGURE D-1 24 VDC BATTERY CHARGER

Performance

Both the charger and the batteries themselves performed without failure throughout the test period.

Suitability

Both charger and batteries are suitable, primarily because of their reliability.

APPENDIX E MAIN STORAGE BATTERY

Purpose

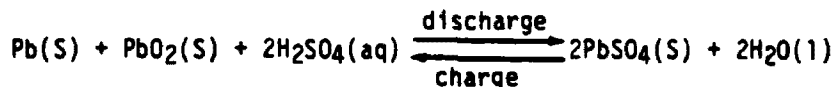
The batteries acted as a deep-cycle energy storage medium. In this system, when the battery bank was fully charged it would assume the complete load. At a predetermined end-of-discharge point, the diesel generator (Appendix 1) would come on line and simultaneously charge the batteries and assume the AC lighthouse load. Any available wind energy was always diverted directly to the batteries regardless whether the battery bank was being charged or discharged. At a predetermined end-of-recharge point, the generator would shut down, and the inverter (Appendix 2) would come on line and the discharge process would begin again. Therefore, the batteries were constantly being cycled over the test period. The batteries are required in a system such as this one because the wind resource is too unpredictable to depend upon it to operate the lighthouse alone (i.e. without diesel or batteries). The alternative of providing a diesel backup for a wind generator (i.e. still no battery storage) would be unsuitable for our application based on the high rate of diesel start/stop cycling even though control options have already been developed by others (Infield, 1984).

Physical Description

The batteries employed in this 120 VDC system, manufactured by GNB, Inc. as model RE5-350, are a flat plate, lead acid (specific gravity of 1.285) design originally intended for traction applications such as fork lifts. Each of the 60 cells (nominal 2.0 V per cell) is rated at 350 ampere-hours (Ah) at the six hour discharge rate and 77°F. But for our particular low discharge rate of about 10 A, the capacity of the cells is about 425 Ah. The eight negative plates are constructed of lead, calcium, and tin while the seven positive plates are of lead, antimony (2%), and cadmium. These cells are sold in 5 cell series wired modules packed tightly in a leak-proof polypropylene tray. Each cell weighs about 50 lbs. and measures approximately 5 in. wide X 6 in. deep X 16 in. in height. The entire battery bank weighs about 3200 lbs.

Battery Theory

At this point, we review some basic battery theory in order to make the remaining portions of this appendix more meaningful. The basic, overall electrochemical processes for charge and discharge of a lead-acid cell can be expressed by the following equation:



When the cell is discharging, lead sulfate is formed at the sponge-lead negative plate and at the lead dioxide positive plates. This sulfate deposition is characterized by the consumption of the sulphuric acid and formation of water during discharge. During charge, the lead sulfate is reconverted back to PbO₂ at the positive plate and lead at the negative plate.

Charging Characteristics

There are many different ordinary methods for recharging a secondary lead acid cell including: two-step constant current, constant current/constant voltage, constant voltage, and combinations of the above (Vinal, 1955). There are also some extraordinary methods such as pulsed charging and gas-sensing (Nowak, 1985). For this system, the charge regime was determined by a commercially available, magnetic amplifier type charger as described in Appendix 3. Figure E-1 reveals a typical charge cycle for these cells. A typical charge period lasted about 18 hours while the corresponding discharge required about 24 hours. The system was designed to allow the diesel to assume the lighthouse load in parallel with the battery charging task. This had several advantages. First, the charging could be accomplished in shorter period since there would be no load demands on the battery. Second, the diesel could be loaded more efficiently. Third, it made the determination of where energy was going within the system easier to determine. As stated earlier, the diesel fully charged the batteries but as full charge was approached, the charge acceptance decreased and more charge energy went into gassing. In other words, an expensive, high-grade power source was used during an inefficient charging period. It would have been convenient if the "free" energy from the wind could have been utilized during this inefficient portion of the charge routine. This wasn't possible for this particular system for two primary reasons. First, the wind regime at this site couldn't reliably support such a charge method since it would not only have to supply the lighthouse load but also provide for the inefficient charging required to fully charge the batteries. Second, at near full charge, the battery bank voltage was above the high voltage limit of the wind generator.

As this energy system was designed, the batteries were typically cycled between 95% state of charge (SOC) and about 45% SOC (as determined by a ratio of input charge to output charge of 1.2; see Appendix G). No provision was made to automatically equalize the individual cells through periodic lengthy overcharging. However, such equalizing recharges were carried out manually, approximately on a monthly basis, by repair/maintenance personnel visiting the site for other reasons. From limited site data and parallel laboratory work (Thacker, 1985), we conclude that these cells operated more or less in a continuous stratified state. These particular cells are advertised as having a lifetime of at least 1500 cycles (80% capacity cycles) (undated Gould sales bulletin entitled, "Gould's Batteries for Renewable Energy Applications"). Since these cells experienced only 50% capacity cycles, they should, according to the manufacturer, last even longer (Gould Renewable Energy Batteries, "Measures of Performance", paragraph D, undated sales literature). In the approximate 50 cycles carried out with these batteries, no discernable loss of capacity has been noted.

As mentioned earlier, manufacturing differences produce cells with differing cell characteristics. Differences in cell characteristics tend to increase over the operational life of the battery, profoundly affecting the charging, maintenance and life of the cells (DeLuca, 1983). For example, a 120 V battery bank might be made up of 60 cells, or 12 modules (5 cells per module). The charging procedure might be tied to the module voltage, such as,

charge at constant current until a particular module voltage is reached then switch to constant current charging to finish out the charge. However, if one of the cells in the module has a lowered charge-voltage characteristic (i.e. declines with age) then the initial constant current charge process must be prolonged to attain the desired module crossover voltage. This would lead to overcharging of the healthier cells with attendant water loss and other undesirable aging effects. In short, conventional charging procedures either totally ignore the presence of weak cells (damaging them) or tailor the charge around the weak cells tending to damage the healthier cells. This implies that in order to prevent costly premature failure and maintain reliability some type of battery management is required. Also, conventional charging methods rely on a preset battery voltage condition for regulating the charging process and not on the ability of the battery to accept charge. Consequently, as the batteries age or change temperature or become electrolyte stratified their voltage characteristic changes unpredictably and conventional chargers simply cannot consistently charge the batteries at optimal efficiency. Charging at optimal efficiency means supplying the battery with as much charge as it will accept without causing electrolytic gassing. The advantage of charging at this variable rate is that it reduces charger (e.g. diesel) operating time and is energy efficient. A method of charging batteries based on battery charge acceptance would be independent of battery age, battery operating temperature, and battery state of charge and would enhance the performance of the battery component in such a system (D. Nowak, UAH Rpt No. 445). However, as mentioned in the theory section above, electrolyte stratification is detrimental to battery life and is usually defeated through gassing. And so two conclusions are reached which are dichotomous. To efficiently charge the battery one desires to reduce the electrolytic gassing but in order to destratify the electrolyte, one desires to create gassing. Ignoring mechanical mixing, it appears that a charge mechanism based on a gassing rate which will just adequately gas the electrolyte is required.

Performance Within the System

To date, these batteries have performed well in this system. No cells have had to be replaced for any reason. Because of the large capacity of these cells and the time required for capacity losses to become detectable, it is too soon to make a judgement on the suitability of these cells for this system based on actual site data. From the battery data collected, the following information is presented:

(1) Battery voltage change during charge - Figure E-2 reveals how the battery bank voltage changed during a typical charge process. The maximum voltage was about 146.6 V (2.44 V per cell) and the minimum on-charge voltage was about 126.7 V, for a charging range of about 20 V. Using a second order, polynomial regression model, the bank voltage during charge can be expressed as function of the charge time:

$$\text{voltage}(t) = 126.56 + 2.528t - 0.0774t^2$$

(2) Battery voltage change during discharge - Figure E-3 reveals how the battery bank voltage changed during a typical discharge process. The voltage maximum was about 131.8 V (2.2 V per cell) while the voltage minimum was about 115.6 V (1.93 V per cell) for a discharge voltage range of about 16 V. This discharge voltage range is important since it indicates that the input to the inverter varies over the course of the discharge. As indicated in Appendix 2, the output of the inverter varied proportional with the input so that, essentially, the load received varying voltage through the discharge period. The effects on the load are discussed in Appendices 2 and 8. The "sawtooth" nature of the discharge curve is due to the 50% duty cycle load. When the load was "on", the bank voltage typically dropped from about 1.0 V at the beginning of the discharge to about 1.5 V near the end of the discharge. The discharge bank voltage at any time, t , can be reasonably expressed as a function of the discharge time:

$$\text{voltage}(t) = 131.98 - 1.0559t + 0.0162t^2$$

(3) Battery state of charge as a function of battery charge voltage - Figure E-4 reveals how state of charge varied with the on-charge battery bank voltage as indicated by the data points. The solid line is a 4th-order polynomial fit to the data. The fit is adequate up to about 92% SOC, and given by the following equation:

$$\text{SOC} = 104641.53474 - 3035.20133 V + 32.91478 V^2 - 0.15814 V^3 + 0.00028421 V^4$$

The linear portion of the curve continues up to about 140 V (85% SOC) and can be approximated by the following linear fit:

$$\text{SOC} = -249.3417 + 2.3923 V$$

(4) Battery state of charge as a function of battery discharge voltage - Figure E-5 indicates how the battery SOC typically changes during a discharge. The continuous line through the data is a second order polynomial fit to the data:

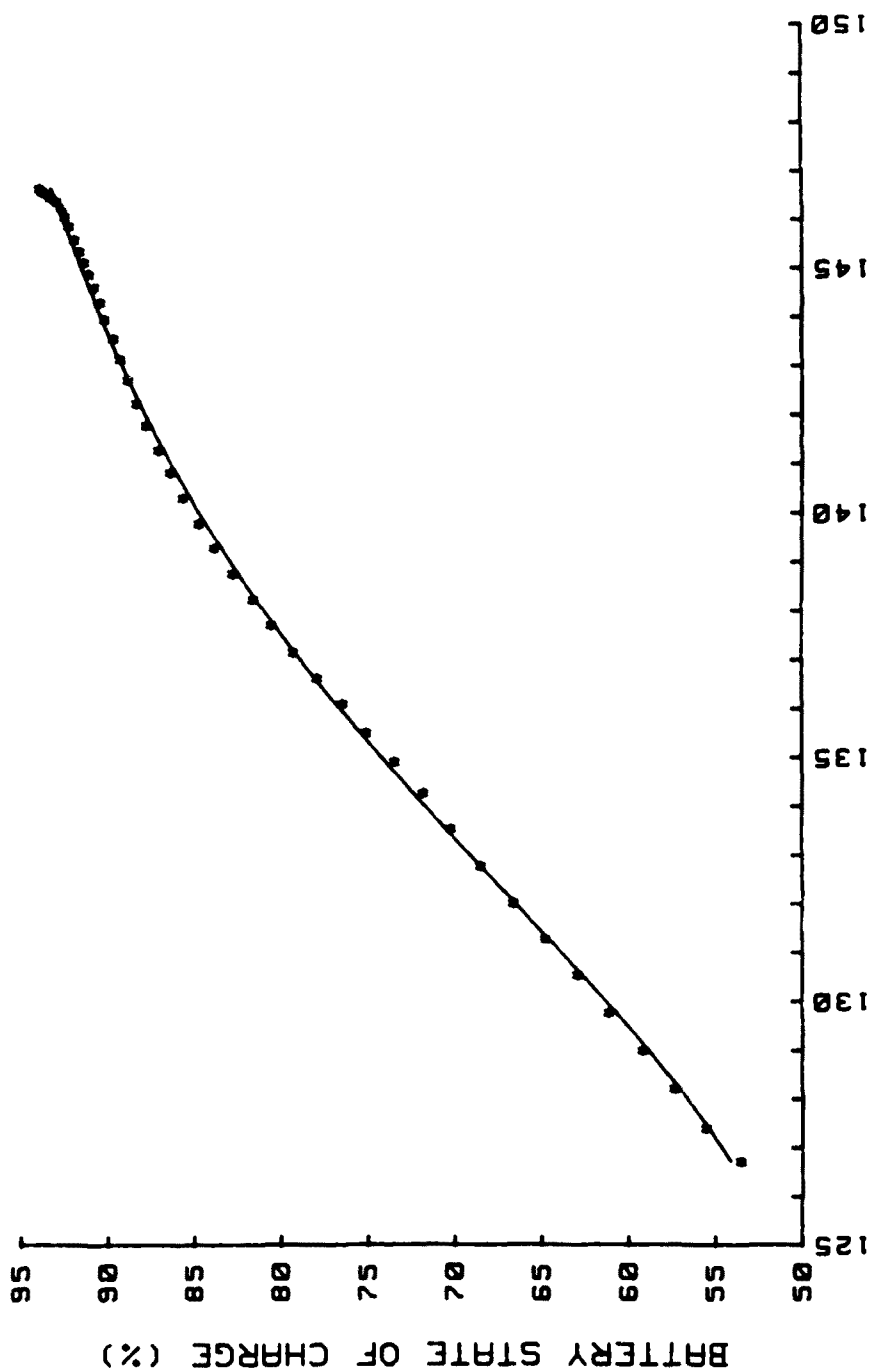
$$\text{SOC} = -1555.00953 + 23.70427 V - 0.08499 V^2$$

(5) Battery current regime - Figure E-6 reveals the flow of current into the batteries (negative values) during charge and out of the batteries during discharge (positive values). Here, the peak current into the batteries during charge is about 31 A with the charge finishing at about 4 A. The 50% duty cycle of the load is also readily apparent. The loaded condition (i.e. light "on") draws about 13 A while the housekeeping load merely draws about 5 A.

Water consumption

Battery water consumption is important for two reasons. First, the frequency of water additions basically determines the maintenance interval of the batteries. Second, the water consumption is a measure of how well the cells are gassing which in turn is a measure of the electrolyte destratification taking place. Of the 60 cells, 12 pilot cells were selected

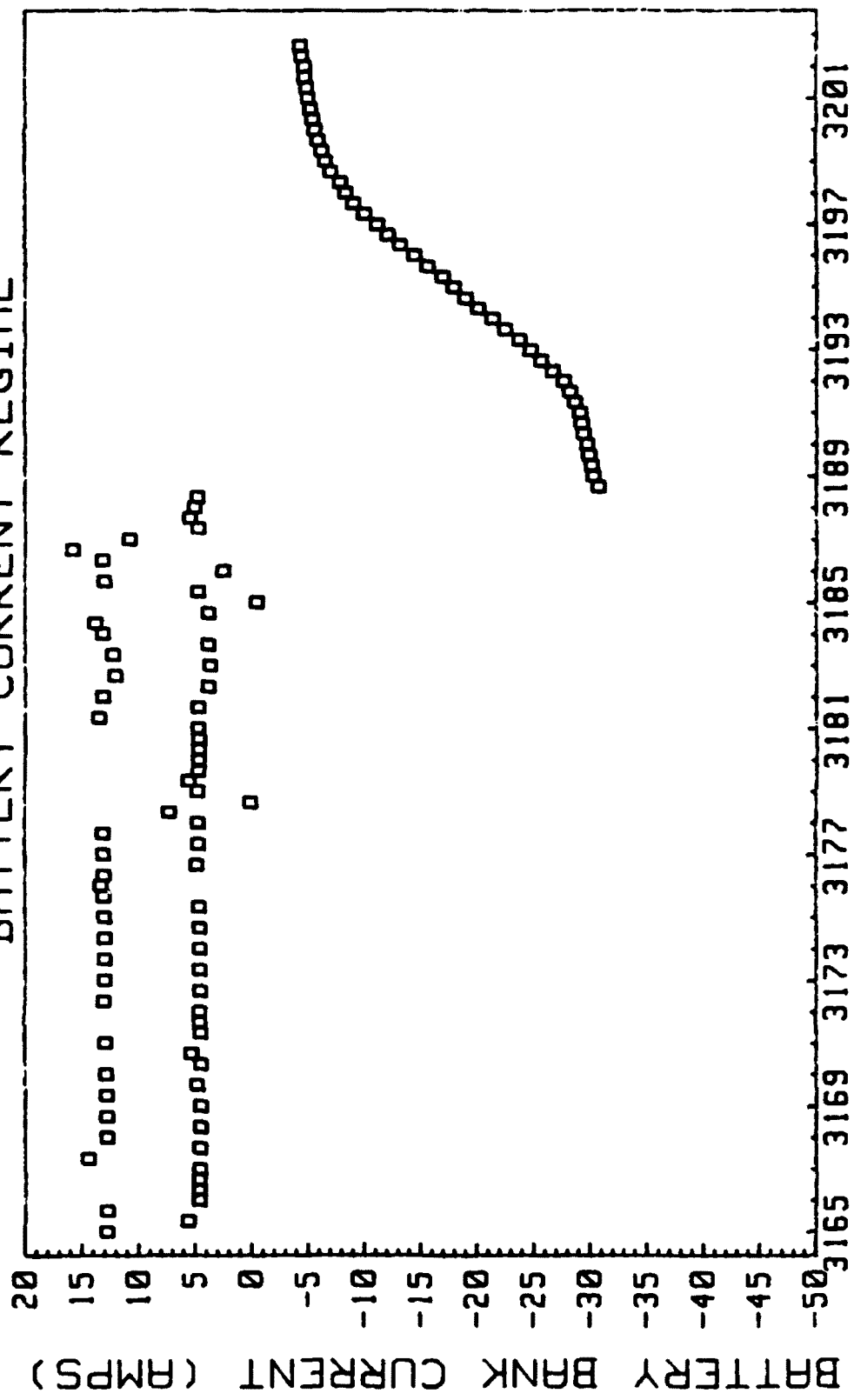
20TH CHARGE



BATTERY BANK VOLTAGE

FIGURE E-4 BATTERY SOC VS VOLTAGE (20TH CHARGE CYCLE)

BATTERY CURRENT REGIME



ELAPSED TIME (HRS)

FIGURE E-6 BATTERY CURRENT REGIME

The Energy Management Prototype Power System (EMPPS) monitored outside temperature, inside temperature and battery temperature. Ideally, electrolyte temperature is desired. However, our apparatus measured the battery casing temperature through a thermocouple epoxied to the top of one of the central cells. This was supposed to represent the electrolyte temperature but in retrospect is inadequate for expressing the true electrolyte temperature since it is located in a convective cooling region and too sensitive to ambient temperature. Figure E-7 is a plot of inside hut temperature, battery temperature and outside temperature all varying with charge/discharge time. The large peaks in the inside hut temperature are due to heat generated by the diesel generator during the charging process. Diesel "on/off" status is indicated by the solid line. Note that the peak inside temperature occurs mid-way through the charging cycle. This inside temperature peak corresponds to about 85% state of charge (SOC). Recall from Figure E-4 that this is the end of the linear portion of the SOC charging curve. Therefore, the hut temperature rises dramatically during the low-SOC, efficient part of the charge curve, peaking at over 100°F. At about 85% SOC, when batteries have begun to gas noticeably, the inside hut temperature begins to decline even though the outside temperature is stable. Meanwhile the battery temperature has continued to climb. Finally, at about 93% SOC, with inside hut temperature still dropping, the diesel shuts off ending the charge cycle. Within 40 minutes, the battery temperature peaks and begins to decline. This well insulated hut requires nearly 20 hours from temperature peak to drop to ambient or about 13.5 hours from diesel shut-off. After the battery temperature peaks (i.e. discharge has begun), its temperature drop is reasonably linear indicating a 10°F drop in temperature every three hours. During the charging process, the battery temperature rises about 100°F and during discharge drops about 60°F, indicating an overall rise in battery temperature of 40°F during the entire charge/discharge period. This is probably due to the increase in outside temperature and not due to lack of recovery time. Due to the low discharge rates, temperature drops during discharge. However, if discharge rates are high (e.g. 100 A) as in electric vehicle applications, the battery temperatures tend to also rise on discharge possibly leading to the phenomenon known as thermal run away. In thermal run away, the high temperatures depress the battery voltage, resulting in more current being supplied (by the charger) to the battery which increases the battery temperature still more. The final result is serious damage to the battery including possibility of explosion. Under our present regime this would not occur.

Battery Selection

The correct choice for the main energy storage battery is perhaps the most critical decision to be made for these stand-alone remote energy systems. No matter what the task, whether starting an automobile, flashing a camera strobe or storing energy for a remote cycle-charge system one must match the battery design to the application. Specifically, a battery designed for deep discharge cycling in the motive power industry isn't necessarily the right battery for our remote, cycle-charge application. In general, the operational requirements for a traction battery are much less stringent than those of the remote cycle-charge application. Our application requires:

- (1) no more than annual maintenance (including water addition)
- (2) low self-discharge rate
- (3) low charge/discharge stratification
- (4) long cycle life at 50% DOD
- (5) ability to withstand large temperature excursions
- (6) internal ruggedness

Ideally, the correct battery design would be the result of a systems design approach for this application. Most end-user research has focused on retrofitting existing batteries to make them more compatible with application needs. In the case of flooded, lead-acid batteries, these retrofits usually involve a stirring or pumping method to destratify the electrolyte and also some scheme to thermally manage the battery. For remote sites, these retrofits tend to be complex and of questionable reliability (Solman, 1982). What is needed is a lead-acid design which has these features already incorporated in it. Additionally, the battery must be correctly sized (capacity) for the task. The available battery capacity will determine to some extent how often the hybrid system will cycle. Battery cost increases with capacity, so large capacity is desired to extend system life and provide reserves but must be balanced with battery cost.

Of course there are other battery technologies which may prove satisfactory. Among those already available, are the Nickel-Cadmium and the gel-cell. Nickel-Cadmium (Nicaid) is attractive because the electrolyte doesn't participate in the main reaction and doesn't stratify. The Nicaid is capable of fast recharging making it desirable from the diesel maintenance point of view. But the Nicaid doesn't perform well under elevated temperatures (greater than 45°C) and cost about twice as much as a comparably sized (250 Ah) conventional deep discharge lead-acid system. Also, the Nicaid could be capacity limited by its "memory effect". The gel cell also limits electrolyte stratification but is sensitive to overcharging. Given these many considerations, the selection of the best battery for the remote site application is not trivial. In fact, system design requirements may suggest different battery technologies depending on the location of the remote site.

APPENDIX F WIND GENERATOR

Purpose

The wind turbine was placed in the energy management system to provide an economical source of power for this system. The wind turbine draws power from the wind and charges the 120 VDC battery bank.

Description

The wind generator employed for this test was manufactured by North Wind Power Company (Box 556, Moretown, VT, 05660), model number HR2. This is a 120 VDC, horizontal axis wind turbine (HAWT) with a three-bladed, upwind rotor capable of about 2.2 kW output at 21 mph (Rocky Flats Performance Summary, 1982). The wind turbine is described below by components.

a. Rotor Blades and Hub Assembly - The blades collect the kinetic energy in the wind and convert it to useful machine power. The rotor assembly specifications are given below:

Weight (blades and hub)	85 lbs.
Blade weight	16 lbs. each
Diameter	16.4 ft.
Capture Area	211.2 sq. ft.
Solidity	0.04
Tip speed ratio	7.5
C_p at rated output	0.41
Blade material	laminated wood composite
Hub Material	cast and wrought steel, ASTM 148-73 (Class 80-50)

These are fixed-pitch blades which use a Variable Axis Rotor Control System (VARCS) to limit the rotational speed in lieu of blade pitch control. The VARCS system allows the rotor and blade assembly to tilt skyward from 8 degrees above the plane of the horizon to 88 degrees. The leading edge of the blades uses helicopter blade tape (North Wind part number 29410) to increase the service life of the blades.

b. Transmission - This is direct drive alternator, (i.e. ratio 1:1). There is no need for a gearbox to match rotor speed with the generator's operating characteristics.

c. Generator - The generator is a 3 phase, twelve-pole alternator using a Lundel-type rotor. The field coil rotates with the alternator shaft. The AC voltage is rectified to DC at the top of the tower for battery charging. The generator specifications are given below.

environment. The wind turbine blades wear most notably at the blade tips. The amount of wear will depend on the specific site but generally blades should be replaced every two to three years. Annually, the blade tape should be inspected and some replacement tape will have to be installed. It would not be unreasonable to have a balanced set of replacement blades on site (or at a local aids-to-navigation repair depot).

Performance

The performance of the wind generator during the period 13 February 1985 to 15 May was unsatisfactory. There were two wind turbine failures, the first occurring at about 2:45 p.m. on 3 May 1985 and the second occurring at about 8:30 p.m. on 15 May 1985. In both cases, the reverse current diode (rated at 150 A) located between the positive battery leg and the wind generator had failed. The failed reverse current diode allowed the battery to discharge current (about 1.7 A) to the wind generator. Voltage spikes created by the inverter are suspected to be the source of the diode failures. Each time the diodes failed, the inverter was also found failed. Other problems occurred outside the February to May time frame mentioned above. In May 1984 (one year before completion of this effort), the field brush/slip ring assembly literally melted due to arcing across adjacent rings. Also, in October 1985, the entire alternator, which had recently been refurbished, was replaced due to a failed field coil. The details of these failures and a detailed account of the operating/maintenance experiences gained at this installation on the North Wind HR2 wind machine will be the subject of a future report.

Figure F-1 details the performance of the HR2 during trials at the Department of Energy's contract test facility at Rocky Flats, Colorado.

Figure F-2 portrays the HR2 output as a function of wind speed. Here, raw data has been plotted with no consideration for battery state of charge. Figure F-3 reveals the wind current output as a function of the battery bank voltage. Note that there is basically no output above 135 V. This is due to the adjustable potentiometer setting of the voltage regulator. For this 60 cell battery, the potentiometer setting is evidently about 2.25 V per cell (135 V/60 cells). The result of this setting is a limitation on when the wind generator is capable of charging the battery. Figure E-2 indicates that on charging, the HR2 was unable to contribute above about 70% SOC. The potentiometer was not adjusted during the course of the experiment in order to keep experimental conditions constant. For future work, the potentiometer will be adjusted upward. The maximum voltage output for this machine was about 142 volts. If higher voltages are desired, special arrangements can be made with North Wind Power Company.

Suitability

The four failures mentioned above are cause for concern. The operational availability during the February to May data collection period was about 96%. While seemingly attractive, this figure is actually unacceptable because it

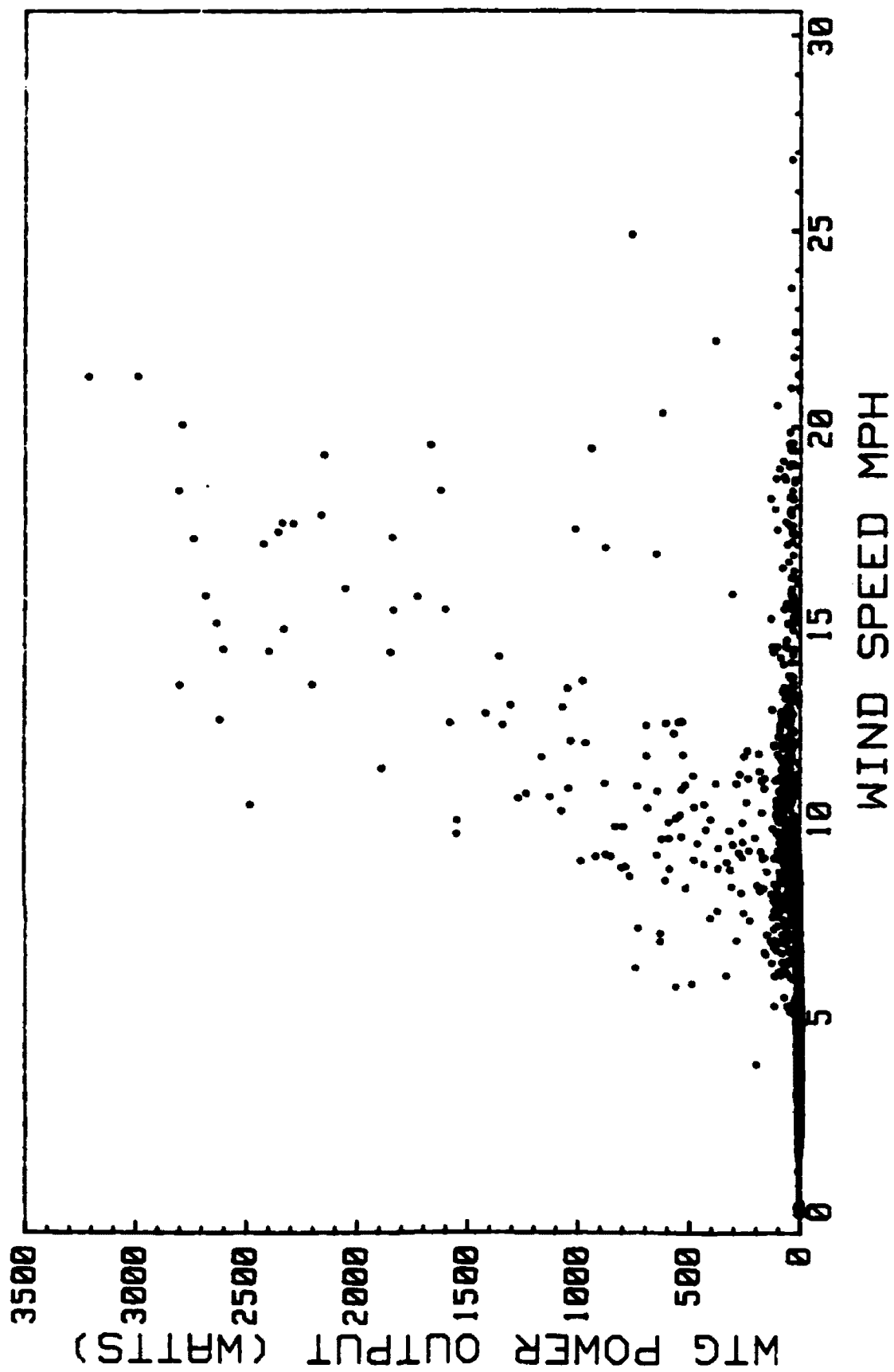


FIGURE F-2 WIND GENERATOR POWER OUTPUT VS WIND SPEED

represents two maintenance visits during a single three month period. The failed reverse current diode is easy and quick to repair, but the two maintenance visits required in the 91 day period is prohibitive. It is likely that the HR2 itself was not responsible for all the failures. Possibly, a lightning stroke or an inverter surge caused the diodes to fail. Nevertheless, the diodes did fail, resulting in unscheduled maintenance visits. The diesel would continue to carry the system after the diode failures, but our data indicates that such failures resulted in a continuous drain on the battery bank of between one and two Amperes, indicating the diodes failed in the closed condition. In such cases, two diodes placed in series would be helpful. The voltage drop across each diode is about one volt, or in other words, a nominal 120 watt loss for each diode. North Wind Power Company has installed such two-diode systems for other customers. If the diode failed in the open condition, then the wind generator would simply freewheel which would result in no damage. In fact, freewheeling by disconnecting the battery is a good means to check and adjust the voltage regulator. It is important to understand the role of a wind generator in this application. To maximize battery life, the battery must be recharged intelligently (refer to Appendix E). The random wind generator output is not capable of meeting the strict recharge regime which calls for specific charge rates at specific times. However, the wind generator is capable of extending the discharge period as illustrated in Figure 3-5, without indefinite partial state of charge cycling. This reduces diesel operating time and once a predetermined state of charge is reached during discharge, the diesel can come on and charge the batteries intelligently; again, reducing diesel operating time. This wind generator is correctly sized since it is not intended in this application to maintain the lighthouse load but merely to assist the diesel in cycle charging the battery. The diesel is considered the prime power source since its regulated charge is required in recharging the battery. This is the correct priority for the power sources since our field experience from Spring 1984 through Winter 1986 indicates that the diesel is more reliable as a power source. Since the wind generator is considered the secondary power source, the loss of the wind generator should allow the system to continue cycling with just the diesel-battery combination. For this particular system, the wind machine represented a reliability problem which exceeded its value as a cost-reducing energy producer, since the wind machine provided, on the average, less than 10% of the load during the 91 day test period and yet had two failures which required maintenance responses. Based on performance from September 1983 until February 1986 (including the February to May 1985 test period), the HR2 is rated unsatisfactory primarily due to the excessive number of failures which is incompatible with the strict reliability requirements of this application. This should not be construed as blanket condemnation of wind generators for this application, nor even of this particular model. The U.S. Navy's experience with wind generators appears to be somewhat similar to our experience, (PAL, 1986). Four wind generators are discussed in the above referenced report. Of the four, only three are reasonably in the same power range as the machine we tested (important for this comparison). Of the three comparative machines, availability data was provided for only two. Of the two remaining machines, one was available 100% of the time during a 9-month test period while the other was available 96.5% during an 18-month period. However, both machines suffered numerous failures outside the test period for

APPENDIX G THE SYSTEM CONTROLLER

Purpose

A model SC-374, Hybrid Power System Controller, manufactured by North Wind Power Co. (Box 556, Moretown, Vt, 05660) was installed in our energy management system. The purpose of such a device is to allow the various system components (wind generator, load, batteries, diesel generator, etc) to interact. This device controls the operation of the system as a whole. The controller has the capability to:

- (1) recognize when the diesel must be started to charge batteries
- (2) recognize when the diesel must be shut down, ending charge
- (3) disconnect load when battery voltage gets too low
- (3) voltage regulate wind generator output
- (4) monitor battery state of charge based on current flow

Basic Components

The SC-374 consists of four basic components which are discussed below.

(1) State of Charge (SOC) meter - This device is a Curtis Model 966 Bipolar Ampere Hour Meter and Controller, manufactured by Curtis Instruments, Inc., (200 Kisco Avenue, Mount Kisco, New York 10549) and is, basically, an analog input, analog output, bipolar DC integrator, integrating signals in the range of 0 mV to 100 mV with respect to time. The bipolar Ah meter converts analog signals to digital (voltage to frequency) in separate charge and discharge channels. The integrated signal is stored in memory. The digital signal is converted to a linear analog DC output signal proportional to the % CAPACITY meter reading on the front panel. The analog output signal range is 0.33 VDC to +/-5.00 VDC (0% to 100% capacity). The output accuracy is +/- 0.1 VDC. Critical to the proper functioning of this device is the selection of the correct charge-to-discharge ratio. This is the means used in the integration to determine how many ampere-hours (Ah) have actually gone into charging or discharging the battery. If this ratio is not fairly accurate, the SOC reading will drift (from the true state of charge) over time. Whenever the batteries are disconnected for system maintenance or repair, the SOC meter should be reset to the known SOC, usually 100% (after an equalization charge). Failure to reset the SOC meter can lead to gross error. This is important because the relays (see below) which control such things as diesel start/stop and load shed are based on the SOC reading. Another important item is the integration memory which is powered by a special 4.0 VDC battery (Curtis part number 12200). This battery failed once and the SOC meter wouldn't return to the correct SOC when the main battery was reconnected. Since the special battery was not available locally, and in any event was extremely difficult to get to, due to its location, the entire Curtis meter was swapped out with a spare which was on hand. It should be noted that these Curtis meters have been specially altered by North Wind for this specific application. These alterations include some logic changes and the addition of temperature sensing.

load until they were exhausted: a potentially devastating occurrence. The loss of the 150 A reverse current diodes (RCD) was disconcerting. To date, the cause of the presumed surges has not been determined. The last RCD failure occurred about 2300 (11:00 p.m.), 3 May 1985 during a discharge cycle. Our data indicates that the AC circuit breaker on the diesel generator tripped at about 1525 (3:25 p.m.) earlier that day. We also have data indicating significant wind current being produced up until the failure. Interestingly, the discharge continued, dragging the battery SOC below 45% (when the "C" relay should have shed the load - but apparently didn't). Finally, at about 32% SOC, the load was shed, presumably because of the presence of the redundant voltage sensitive relays designed to backup the "C" relay. The loss of the RCD is a maintenance item that would have required immediate response. The loss of the voltage regulation fuse results in zero wind generator output; not an immediate maintenance visit since the system could operate as a diesel/battery cycle charge system.

Based on the foregoing discussion, the SC-374 is deemed not suitable for this application. Particularly damning is its reliance on an adjustable charge/discharge ratio to calculate battery SOC with its required drift calibration. As stated earlier, this quantity changes substantially over the life of the battery. At remote sites, it is not practical to suggest adjusting this ratio, particularly since it is battery/site specific. It is also impractical to suggest that before each battery bank is installed at a remote site, a 20-cycle break-in period be carried out after which the proper ratio be determined. There must be a better way to determine the battery SOC. This better way should be a direct measure of the electrochemical process taking place. As the battery ages and the electrochemical processes reflect those changes, then the SOC determination would change accordingly. Perhaps a measurement of oxygen evolution is appropriate. When the oxygen evolved reaches 33% of the total gas evolved, then the charge acceptance is very low and all charge is going into electrolysis (two parts hydrogen, one part oxygen) indicating the battery is fully charged. Perhaps gassing rate can be correlated with internal resistance and that measure used. In any event, the ampere-hour counting technique is suitable for the traction industry where access is daily but unsuitable for an application requiring annual visits.

APPENDIX H SYSTEM LOADS

Purpose

This appendix describes the alternating current loads for which the Energy Management Prototype Power System (EMPPS) supplied power. These AC loads were located in the Cape Henry Lighthouse situated about 200 ft. from the EMPPS shelter.

Description

The following loads were supplied by the EMPPS system:

(1) 1000 watt, tungsten halogen lamp; this lamp was located in a non-rotating, second order classical lens. This lamp is the main visual signal for the lighthouse and operated on a 50% duty cycle.

(2) A standard Lighthouse Automation and Modernization Program (LAMP) 12 V battery charger to charge the Nicad emergency light energy storage battery; the maximum draw for the charger is 850 watts, but since the battery is kept on float charge the load is rarely above 100 watts.

(3) Halon fire suppression system; this draws about 10 watts.

(4) The audio/visual controller (ADC) which acts as a sensor to detect whether the main light signal or sound signal is operative; this sensor system draws about 80 watts.

(5) The Remote Control Monitoring System (RCMS) which floats off the 12 volt charger; this draws about 30 watts;

(6) Fluorescent interior lighting; these drew about 160 watts.

(7) Power transfer switch; this switch was in the system to cut the lighthouse over to available commercial power should the EMPPS hut fail. This switch drew less than 50 watts

The total, relatively constant, "housekeeping" load (i.e. when the 1000 watt lamp wasn't on) was about 350 watts.

APPENDIX I PLASTIDOME

Purpose

The plastidome is an equipment shelter that serves as an integral weathertight structure to house the Energy Management Prototype Power System (EMPPS), including major power components, control circuitry, and distribution busses.

Description

The plastidome is manufactured by Andrew Structures Corporation (9300 N.E. Underground Dr, P.O. Box 11280, Kansas City, MO., 64141, 816-453-6000). Prior to 1983 and their acquisition by Andrew Structures, these shelters were manufactured by the Grasis Corporation (hence are often referred to as "Grasis Huts" in Coast Guard literature). The plastidome is designed to be portable and modular allowing for completed systems to be preassembled and delivered to remote sites with a minimum of on-site construction. These shelters come in a variety of configurations and sizes. Model ES1016-9 (serial no. P82-132-01), was used for this test. Its construction consists primarily of two layered, individually molded, fiberglass-reinforced polyester (FRP) shells. Sandwiched between the outer and inner shells are reinforcing ribs, wood blocking, and urethane foam for insulation. The floor is of similar sandwich design utilizing preserved wood and urethane. The floor is attached to two steel C-channels that run the length of the building and act as its joists support. The uni-body shell is then attached to the floor structure. The following pertinent specifications are provided:

Length	16 ft.
Width	10 ft.
Height	9 ft.
Weight (loaded)	12,000 lb.
Construction	FRP
Finish	white (Gelcoat 944-W334)
Floor	Plywood (with red epoxy finish)
Door Size	3 ft. X 6.75 ft.
Blocking	3/4 in. plywood

Figure I-1 is a drawing of the shelter interior as it was configured for this test (viewed from entrance). The only maintenance for this shelter is a recommended annual washing and waxing.

Performance

The plasidome shelter is an effective housing for the EMPPS. Its advantages include:

- (1) modularity
- (2) structural strength and durability
- (3) low heat loss to environment
- (4) virtually maintenance free

However, its size and weight require special considerations:

(1) a crane appears the only reasonable method for rigging; we used a 15 ton, 60 ft. boom crane (also used to erect the wind tower)

(2) steel lifting cables or slings and spreader bars are required

(3) continental overland travel requires a flatbed truck with over-size travel permits

(4) the foundation, if different from the manufacturer's specifications, must be level because the shelter itself contains no provisions for levelling

(5) Figure I-2 gives the shelter foundation plan and Figure I-3 gives the foundation pier detail

(6) a stoop similar to Figure I-4 is required

(7) Figure I-5 reveals the pier tie down detail

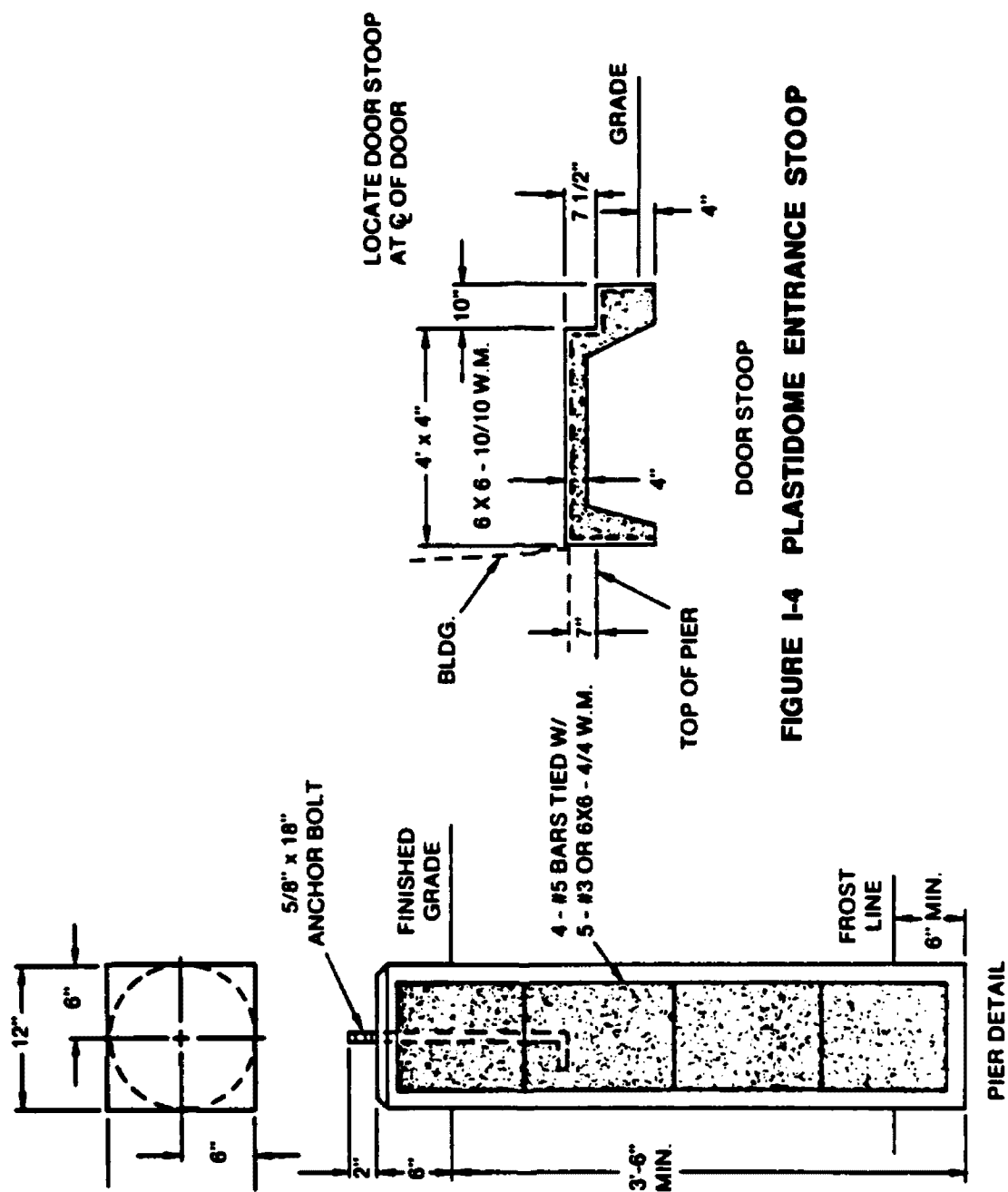


FIGURE I-4 PLASTIDOME ENTRANCE STOOP

FIGURE I-3 PLASTIDOME PIER FOUNDATION

APPENDIX J PROTOTYPE POWER SYSTEM INSTALLATION

Purpose

The purpose of this appendix is to provide insight into what is involved in preparing a site for an energy management power system. Such a system was installed, including a wind generator tower, at the United States Coast Guard Research and Development Center in August 1985. These comments are based on the experiences gained during that installation.

Overview

Installation of the Energy Management Prototype Power System (EMPPS) required moderate amounts of heavy construction, mostly due to the foundation of the wind tower. Equipment was utilized that may not be available at remote sites, including: backhoe for excavation, cement trucks for pouring foundations, and cranes for tower and wind generator installation. Design and engineering considerations are definitely site-specific. Our site was easily accessible and therefore, all footings and foundations were installed per manufacturer's specifications. Some remote sites will require engineering alterations of these specifications.

Field Observations

(1) EMPPS definition - This includes a physical listing of each hardware component including such parameters as size and weight. The physical layout of the shelter components can be arranged as desired but special considerations should be made for the batteries as discussed in Appendices E and O.

(2) Site selection - Although the general site for installation of the EMPPS shelter may be apparent, environmental and possibly political considerations may come into play. Wind generators are particularly sensitive to site selection. Also, the presence of ledge rock complicates foundation installation. Consideration should be given to ease of fuel delivery.

(3) Site layout - A successful installation often depends heavily on how well thought out the contractor's statement of work is. In our case, the installation work was divided into two parts. A general construction contractor was hired to build the required foundations while the manufacturer of the wind machine was hired to actually install the wind machine at the top of the tower.

(4) Site preparation - Site preparation was completed by the general construction contractor during the second and third weeks of August 1985 by a two man crew. The foundation pit for the wind generator was dug (approximately 15 ft. X 15 ft. X 5 ft.) using a backhoe which required about six hours. Some hand digging was required. Standard four ft. concrete forms were constructed in this pit to meet the requirements of the tower manufacturer, Unarco-Rohn (drawing no. C811092 and 8841300). Reinforcing rod,

APPENDIX K SYSTEM SCHEMATICS

The following system schematics are provided for further information.

Figure K-1.a and K-1.b are general system diagrams as viewed from above.

Figure K-2 is a diagram depicting the wire size required for the various components.

Figure K-3 describes the layout of the fire suppression system.

Figure K-4 is a diagram of the 24 VDC battery charger connections.

Figure K-5 reveals the diesel wiring connections.

Figure K-6 diagrams the wiring for the main battery charger.

Figure K-7 indicates the connections in the load contactor box.

Figure K-8 diagrams the system controller connections.

Figure K-9 is a diagram of the diesel load center.

Figure K-10 is a diagram of the AC lighthouse load center.

Figure K-11 is a diagram of the system power flow.

Figure K-12 is a diagram of the diesel automatic starter briefcase.

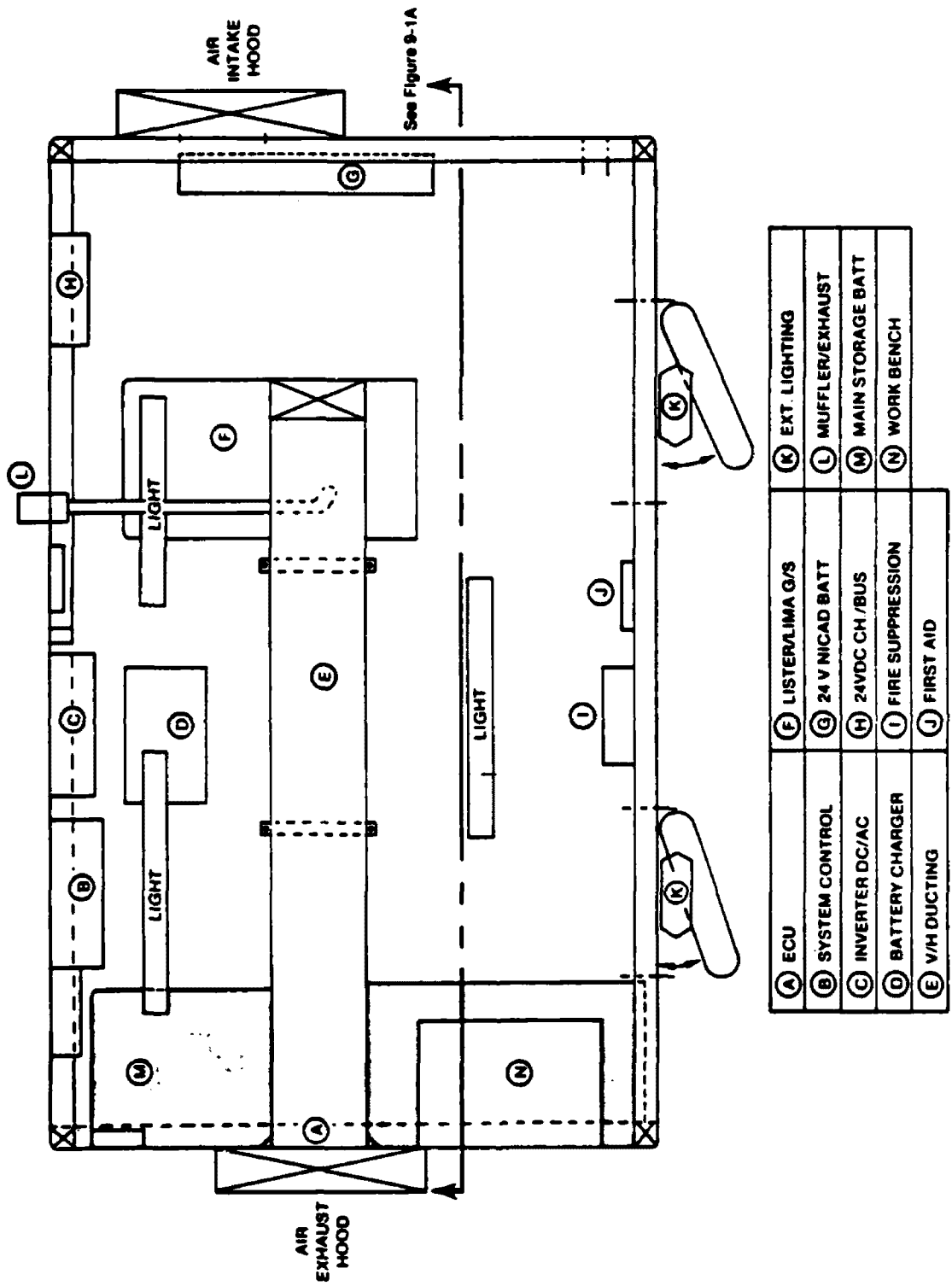


FIGURE K-1.b PLASTIDOME COMPONENT CONFIGURATION

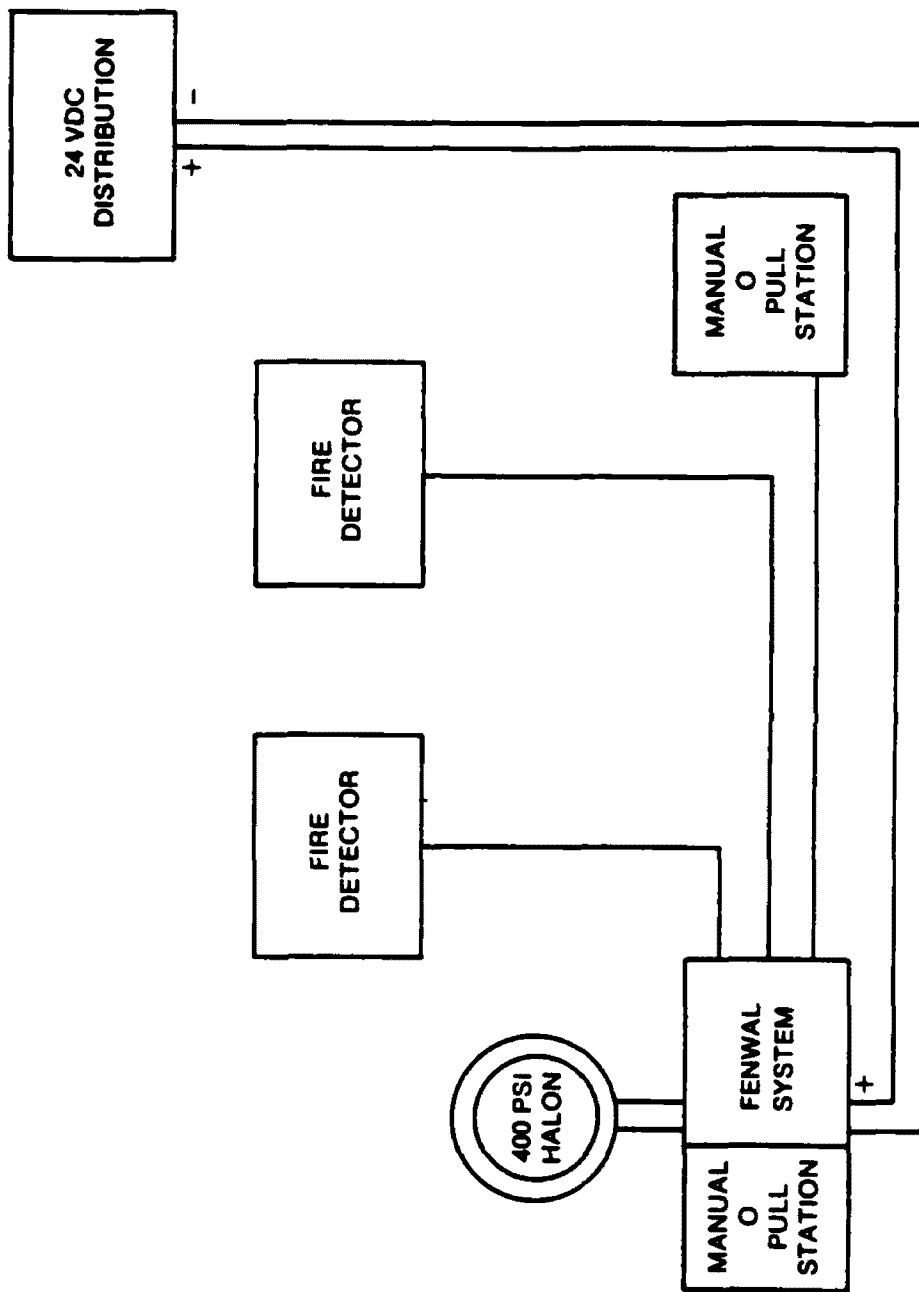


FIGURE K-3 FIRE EXTINGUISHING SYSTEM

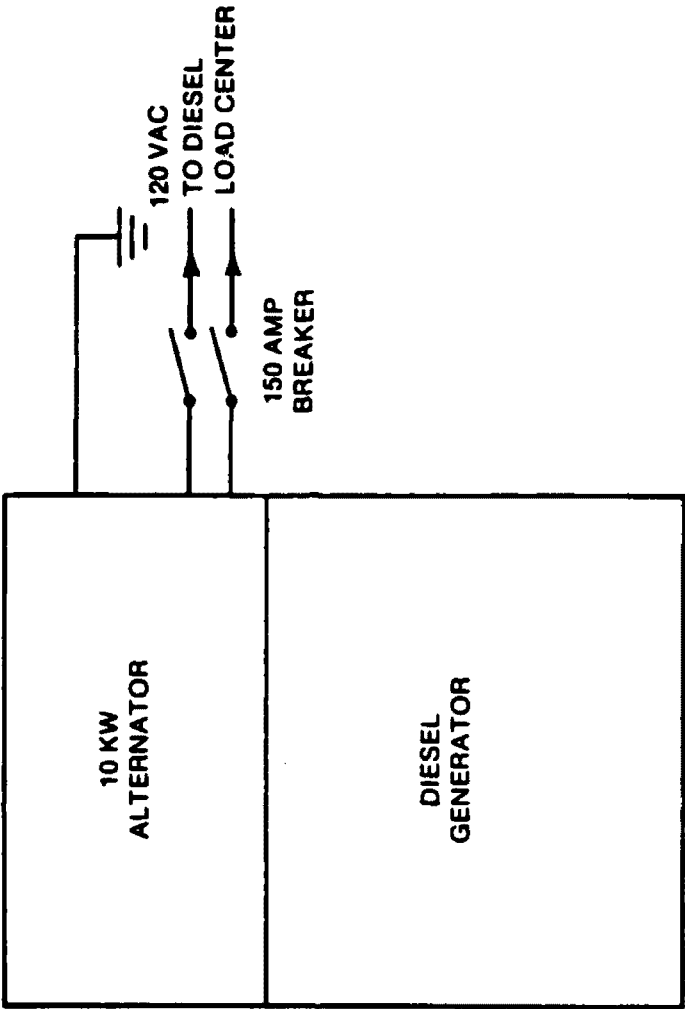


FIGURE K-5 DIESEL GENERATOR CONNECTIONS

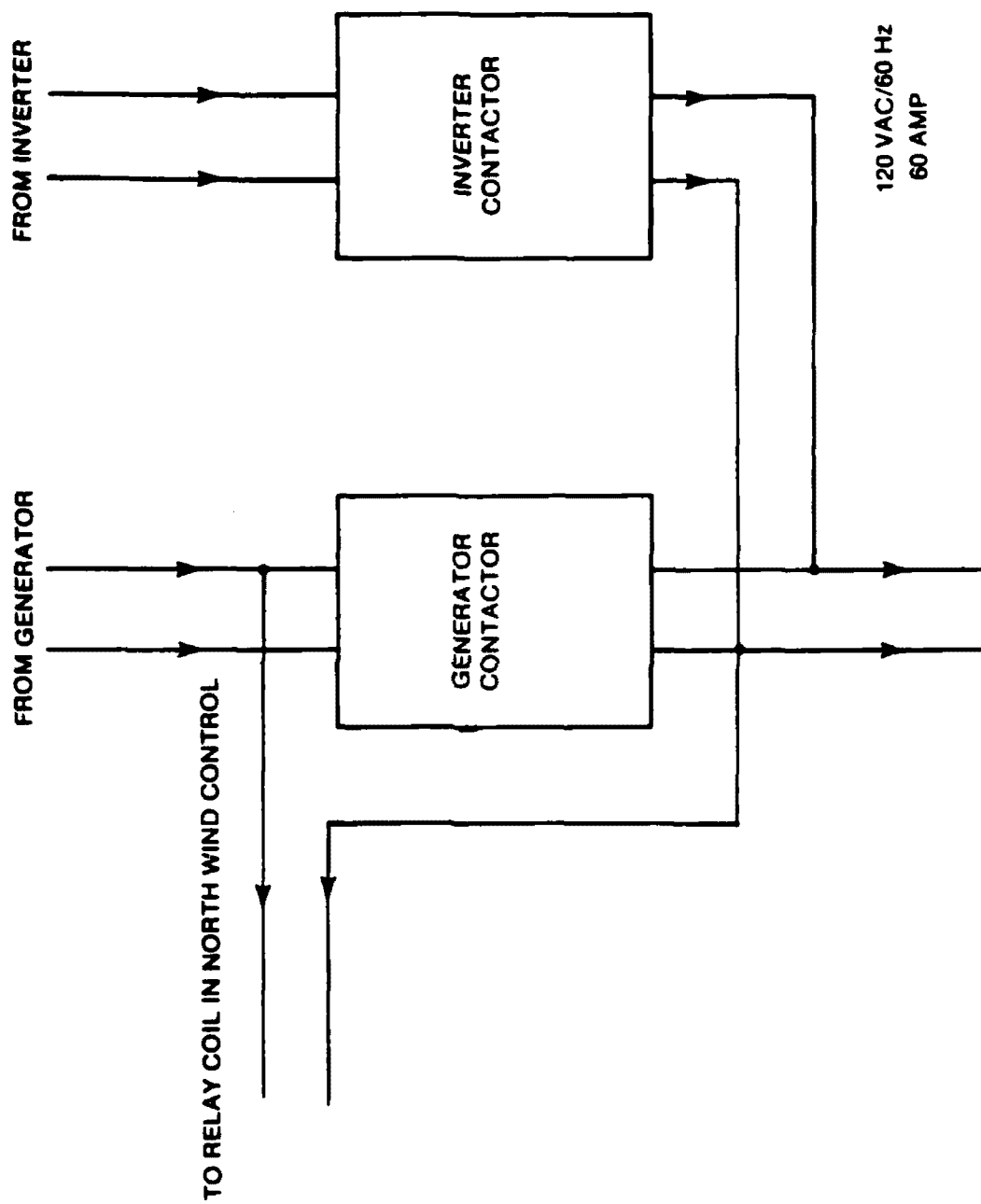


FIGURE K-7 LOAD CONTACTOR BOX

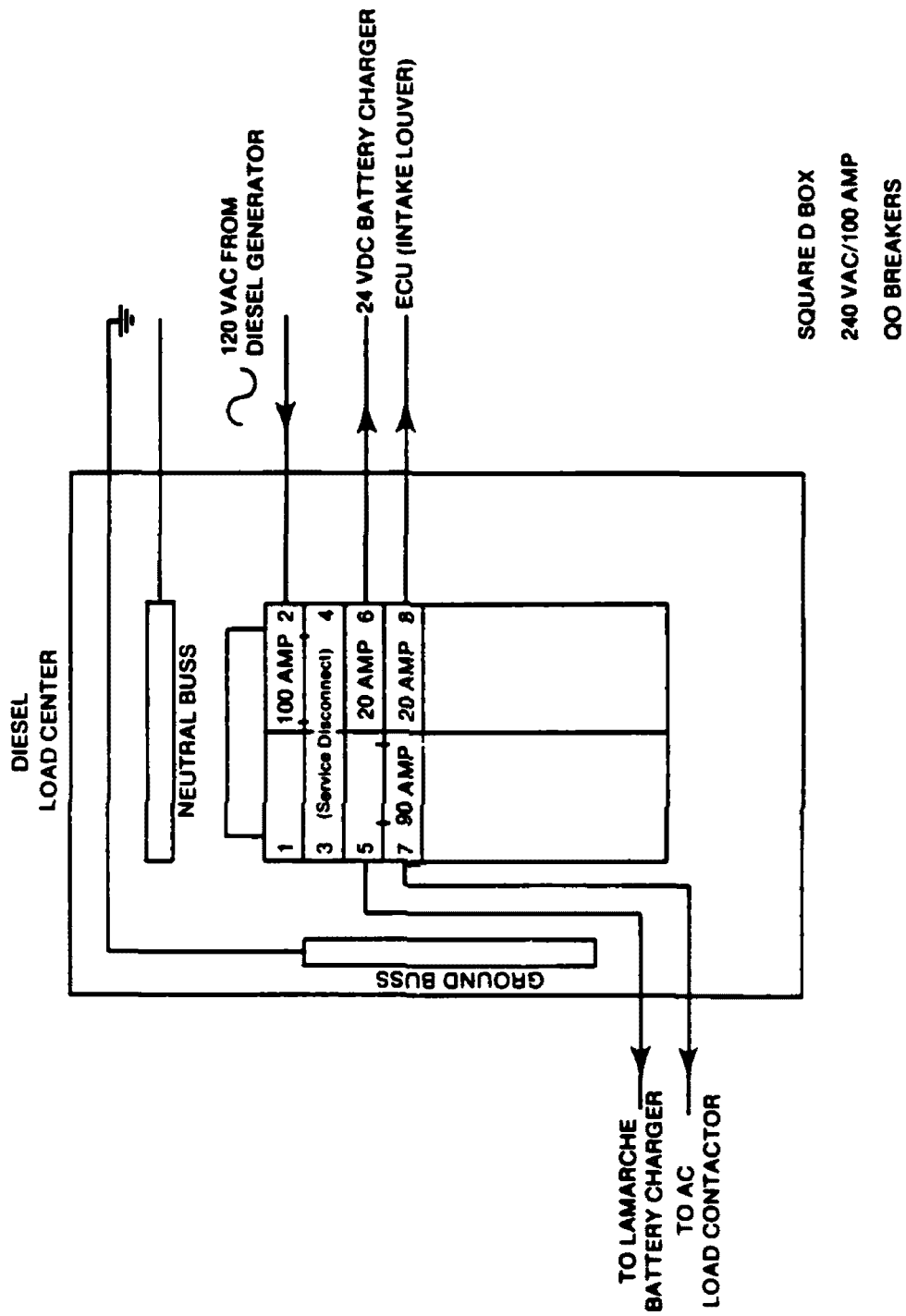


FIGURE K-9 DIESEL LOAD CENTER

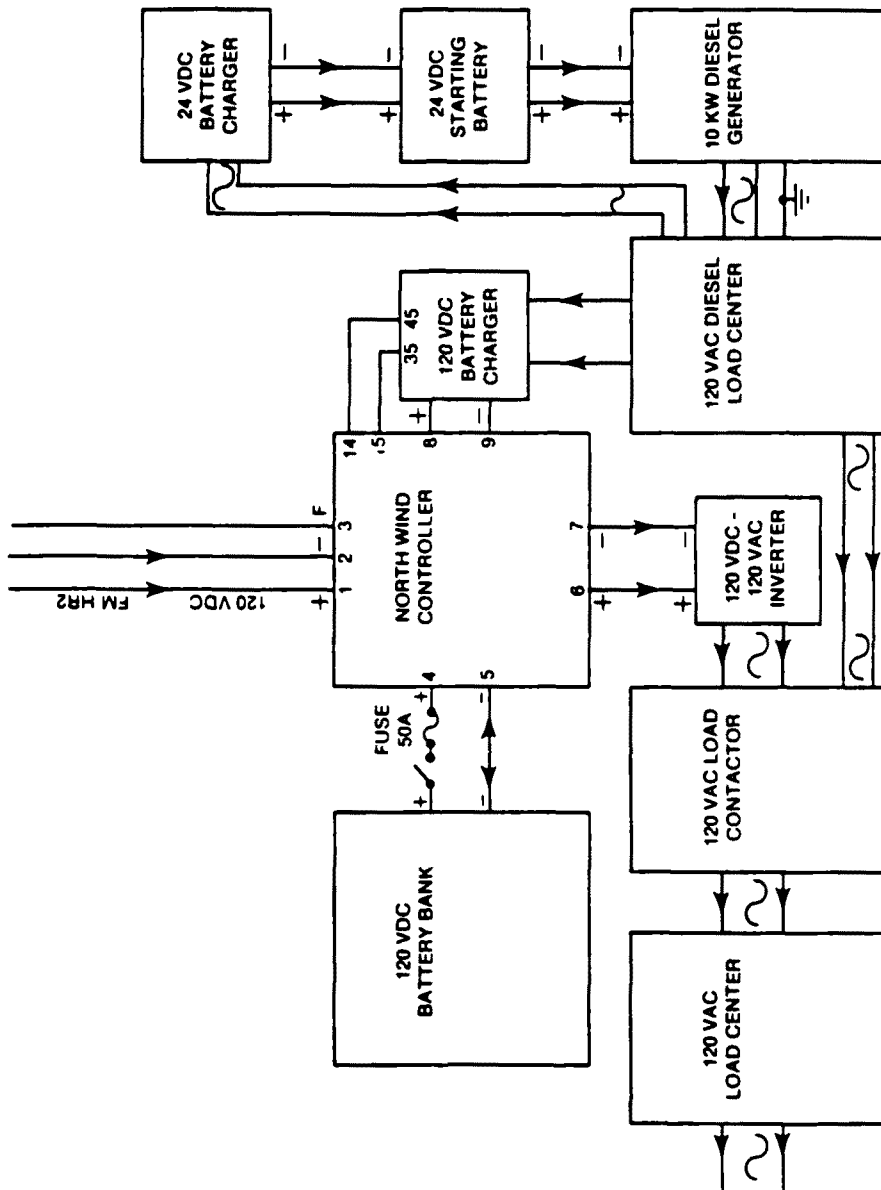


FIGURE K-11 SYSTEM POWER FLOW

APPENDIX L DATA COLLECTION

Purpose

A Fluke Model 2280A Data Logger (John Fluke Mfg. Co., P.O. Box C9090, Everett, WA 98206) was installed at the site to collect specified data at specified intervals. Remote interrogation provided the data on which this report is based. The data collection system includes all equipment necessary to sense, collect, store, transmit and file the data. Figure L-1 is a block diagram of the information flow. Each component is discussed below.

Sensors

A descriptive list of the sensors used in support of this work is given below. Refer to Figure L-2 for the locations of the various sensors within the energy management system, excluding those shown in Figure 2-3.

(1) Direct Current Sensors - For Direct Current (DC) readings, 100 mV, 50 A shunts were used (i.e. a 100 mV reading across the shunt indicated 50 A current flow). The nondirectional current sensors provided vital information on how much DC charge was flowing during the course of the experiment. These were extremely reliable and no failures occurred among these sensors during the course of the experiment.

TABLE L-1 SENSOR LOCATIONS

TA	Wind speed, wind direction
TB	Wind current
TC	Battery temperature, voltage, current
TD	Inverter current
TE	Charger current
MISC	Inside/outside temperature
TF	Battery State of Charge
TG	Inverter on/diesel on
TH	Generator AC to LOAD

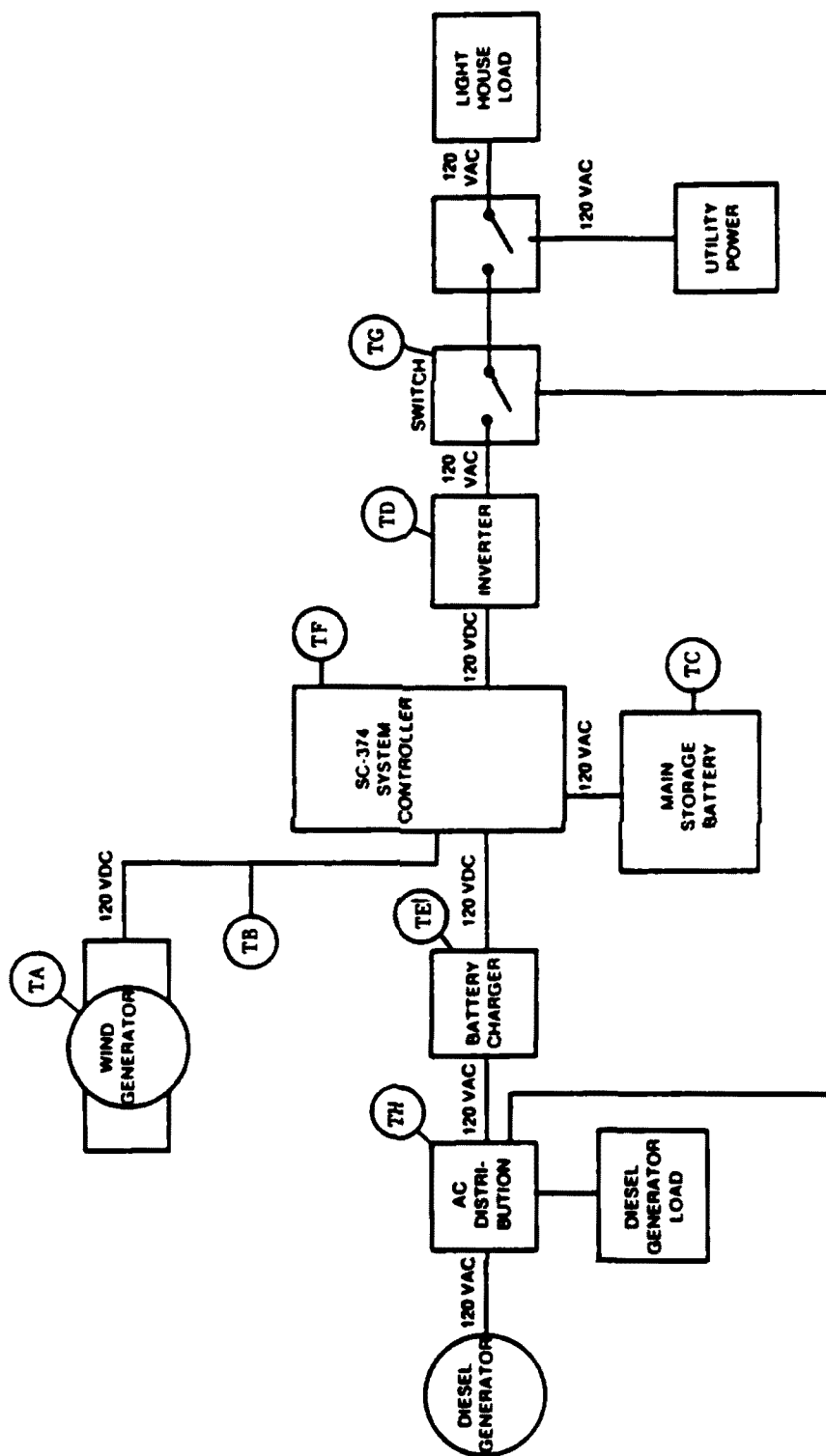


FIGURE L-2 LOCATIONS OF SENSORS (SEE TABLE L-1)

(4) Temperature Sensors - There were two temperature sensors suspended from the ceiling of the plastidome to measure inside temperature. Similarly, a sensor was epoxied to the top of one of the battery cells in an attempt to get electrolyte temperature data as discussed in Appendix E. Finally, there were two sensors positioned in the crawl space under the plastidome to record outside air temperature. These solid state sensors, model AD590, in a TO 52 case, were manufactured by Omega Engineering Inc. (One Omega Dr., Box 4047, Stamford, CT 06907). The linear current output over a range of -55°C to 150°C required a +4 VDC to +30 VDC input. These sensors have a long term drift of +/- 0.1°C per month. The calibration error of this J type sensor is +/- 50°C but the repeatability is excellent at +/- 0.1°C. No failures of these sensors occurred during the test period.

(5) Watt-Hour Transducers - Eight watt-hour meters were installed in the system to monitor energy flow including transients not picked up during normal data sampling. These transducers, Model WH70-2283, were manufactured by Ohio Semitronics, Inc. They were factory calibrated for DC and 60 Hz and supplied with a current sensor calibrated for that particular transducer. Electrical energy is the time integral of the electrical power. In these transducers the integration is carried out using a precision electronic solid state voltage to frequency converter. An analog voltage ramp (0 to 5 VDC) was output to the data logger. Each ramp peak constituted 1 kwh. Instantaneous power and accumulated watt- hours were available on the front of the meter in the form of LCD and LED readouts. There were numerous reliability problems with the front panel meter displays due to faulty factory wiring. Additionally, one of the watt-hour meters failed to give an analog ramp output to the data logger. This resulted in missing data on the output side of the battery charger where the current sensor was located.

(6) Status Lines - Several status lines were available to the data logger and were normally hooked up to status relays in the system:

a. Diesel Start - Indicates that the system controller, North Wind Model SC374, has directed the diesel to start.

b. Diesel Status - Indicates whether diesel started after receiving command to do so.

c. Diesel AC to Load - Indicates whether real power is being delivered by the diesel to the load.

d. Inverter Output Status - Indicates whether or not inverter is supplying power to the AC load.

e. Inverter On/Off - Indicates whether or not inverter is on. The inverter could be "on", drawing about 350 watts, without supplying the AC load.

SCAN GROUP NUMBER = 1
SELECT RUN MODE OPERATION

!BEGIN SCAN GROUP 1 20 MAR 85 07:23:27
FULL DATA

C	0	BATTERY #1 TEMP	60.28	11
C	1	BATTERY #2 TEMP	60.25	DEG F
C	2	BATTERY #3 TEMP	59.92	DEG F
C	3	BATTERY #4 TEMP	59.37	DEG F
C	4	BATTERY #5 TEMP	61.50	DEG F
C	5	BATTERY #6 TEMP	60.21	DEG F
C	6	BATTERY #7 TEMP	59.03	DEG F
C	7	BATTERY #8 TEMP	61.26	DEG F
C	8	BATTERY #9 TEMP	57.88	DEG F
C	9	BATTERY#10 TEMP	58.11	DEG F
C	10	BATTERY#11 TEMP	58.19	DEG F
C	11	BATTERY#12 TEMP	59.86	DEG F
C	12	INSIDE TEMP #1	73.03	DEG F
C	13	INSIDE TEMP #2	69.69	DEG F
C	14	OUTSIDE TEMP #1	41.74	DEG F
C	15	OUTSIDE TEMP #2	48.39	DEG F
C	20	BATTERY VOLTAGE	12.45	VOLTS
C	21	BATTERY VOLTAGE	12.09	VOLTS
C	22	BATTERY VOLTAGE	12.09	VOLTS
C	23	BATTERY VOLTAGE	12.09	VOLTS
C	24	BATTERY VOLTAGE	12.16	VOLTS
C	25	BATTERY VOLTAGE	12.13	VOLTS
C	26	BATTERY VOLTAGE	12.16	VOLTS
C	27	BATTERY VOLTAGE	12.24	VOLTS
C	28	BATTERY VOLTAGE	12.21	VOLTS
C	29	BATTERY VOLTAGE	12.16	VOLTS
C	30	BATTERY VOLTAGE	12.16	VOLTS
C	31	BATTERY VOLTAGE	12.16	VOLTS
C	32	BANK VOLTAGE	146.09	VOLTS
C	33	STATE OF CHARGE	89.72	%
C	34	INV CURRENT	2.74	AMPS
C	35	WIND CURRENT	0.41	AMPS
C	36	CHARGER CURRENT	3.04	AMPS
C	37	LOAD POWER	1455.2	WATTS
C	60	LOAD VOLTAGE	127.06	VOLTS
C	37	BANK POWER	-162.06	WATTS
C	38	BANK VOLTAGE	4.5294	VOLTS
C	80	GENERATR ON/OFF	1.0	
C	81	INVERTER ON/OFF	1.0	
C	82	INV AC TO LOAD	0.0	
C	83	GEN AC TO LOAD	1.0	
C	84	DIESEL START	1.0	

END SCAN GROUP 1 20 MAR 85 07:23:43

*

SELECT RUN MODE OPERATION

FIGURE L-3 DATA SCAN GROUP (EXPANDED FORMAT)

A single scan group contained the data for as many as 45 variables for a single point in time. A typical data dump from the remote site might contain 300 scan groups (a scan group is taken every 20 minutes). The data were received in serial format with special imbedded characters to separate scan groups, and stored in a large data matrix (one scan group per row) using software developed for that purpose. Each scan group was then sequentially entered, the data retrieved by variable and refiled in a time sequential file for each variable, again, using software especially developed for that purpose. In other words, the raw data were brought in, sorted, and refiled in separate time sequential variable files. About 45 binary data (BDAT) files were created to store the sequential data in. The file structure is one data value, or real number, (which is equal to 8 bytes) per file record. This allows for convenient random accessing of the BDAT file to pick out particular variables at specific times. Since there are 4525 data values per variable, it follows that each time sequenced variable file contains 4525 records. The data files are all correlated in time. For example, if one entered the battery bank voltage file at the 200th record, one could then retrieve the wind generator output at that same time by entering the 200th record of the wind generator output file. To find out the actual time of these data points, one would simply enter the elapsed time file at the 200th record and read the elapsed time value (recorded in hours). The start time from which all elapsed time is calculated is 0000, 1 January 1985. It should be noted that in a field-deployable hybrid energy system, some remote monitoring and control will be required. Monitoring could possibly allow prediction of failure. For example, continual decreasing cycle time could indicate loss of battery capacity. Control features could allow temporary solutions (e.g., 24-hour diesel operation) until corrective maintenance could be carried out.

APPENDIX M SAMPLE DATA PLOTS

Sample data plots are provided for general information. The sample plots are taken from the 22nd charge/discharge cycle during the period, 12-13 May 1985.

Figure M-1 is a plot of main storage battery state of charge (SOC) as a function of elapsed time over the entire charge/discharge period. The minimum SOC is 50% while the maximum is about 94%. The length of charge is about 12.5-hours while the discharge lasted about 23 hours. A least-squares fit to the discharge curve is given by:

$$\% \text{ SOC} = 6024.029 - 1.874 t$$

where t = the elapsed time value of the axis of abscissa.

Figure M-2 is a plot of three temperatures. The square data point symbols represent the temperature (°F) inside the plastidome shelter. The circular data point symbols represent the battery temperature as experienced by a sensor epoxied to the top of the cell casing. The triangular data point symbols represent the outside air temperature. The maximum shelter interior temperature was about 104°F. Once discharge has commenced, it takes about 13 hours for the inside temperature to drop to the outside temperature level. The battery temperature peaks at the cessation of the charge cycle and begins to drop slowly but during the 23 hour discharge period approaches within only 12°F of the ambient temperature. Refer to the discussion of battery thermal management under Appendix 5.

Figure M-3 is a plot of the power in watts consumed by the load during the charge/discharge cycle. The maximum power consumed, associated with the lighted condition of the lamp, is about 1400 watts. The low power data is indicative of a lamp off condition and reveals a housekeeping load of about 400-watts. The decline in the power over the discharge period is explained by the decreasing battery bank voltage.

Figure M-4 is a plot of battery bank voltage over the charge/discharge period. During charge the battery voltage ranges from about 127 VDC to about 146 VDC. Similarly, during discharge the battery voltage ranges from about 132 VDC to about 115 VDC. Therefore, the entire swing of battery bank voltage ranges from 115 VDC to 146 VDC. Of course this range is based on the settings of the SOC meter since charging and discharging cease when a predetermined SOC has been reached.

Figure M-5 is a plot of load voltage as a function of charge/discharge time. During charge, when the diesel is supplying power to the load, the load voltage rises from about 125 VAC to about 128 VAC. During discharge, when the inverter is supplying power to the load, the load voltage is seen to drop to under 122 VAC when the lamp is on. According to Table 3-2, U. S. Coast Guard Commandant Instruction M16510.2 (Luminous Intensities of Aids to Navigation

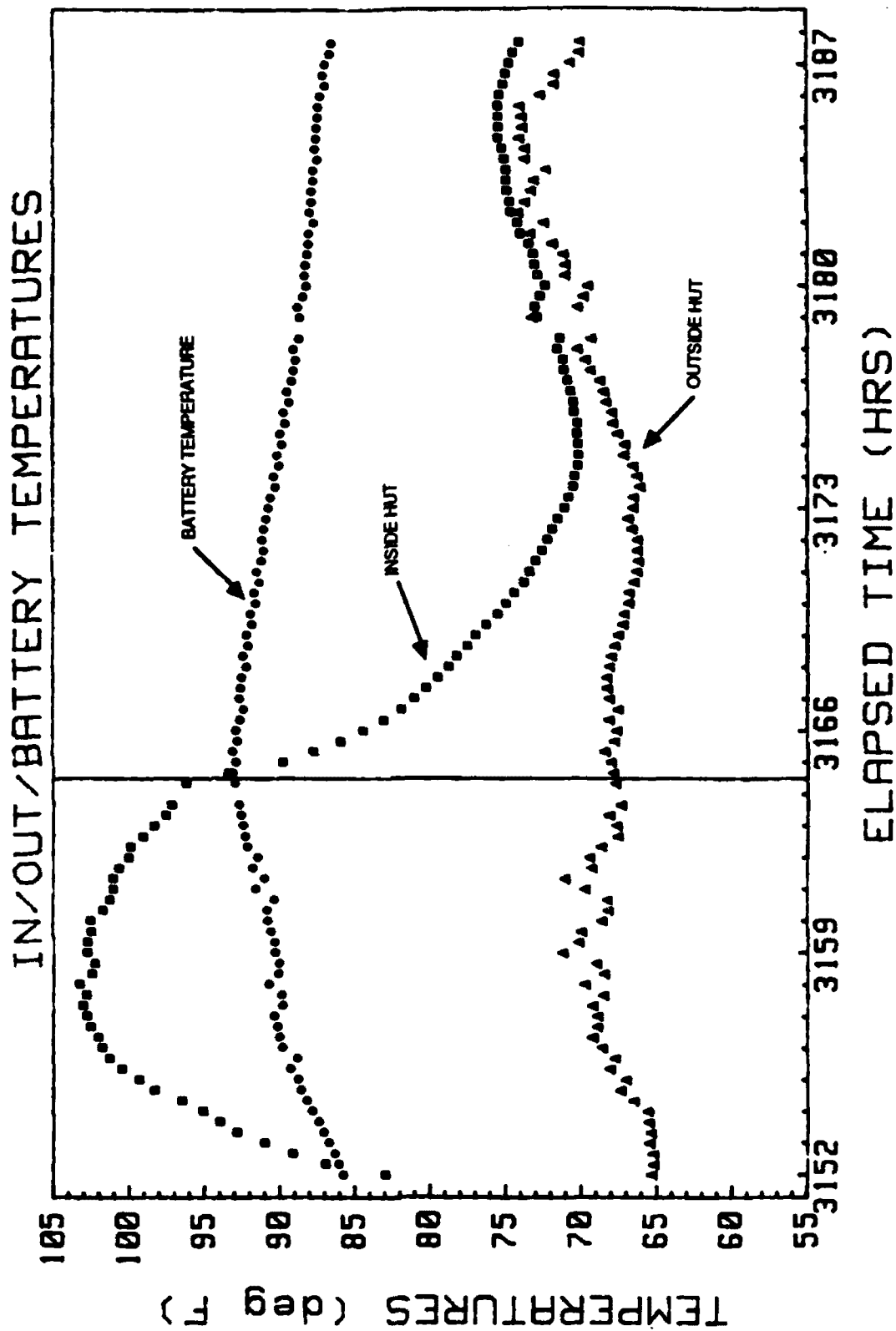


FIGURE M-2 INTERIOR/EXTERIOR BATTERY TEMPERATURES

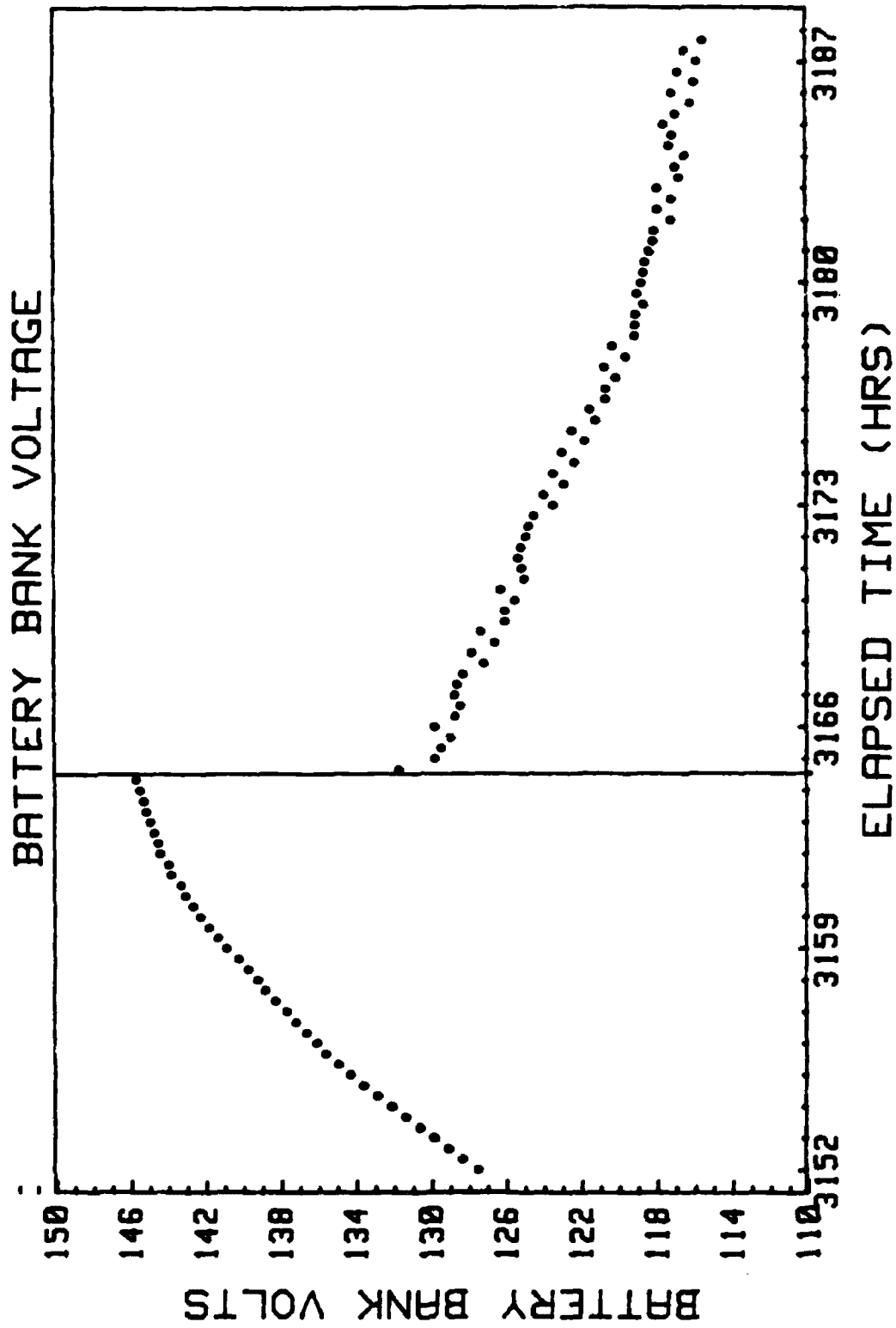


FIGURE M-4 BATTERY BANK VOLTAGE OVER CYCLE

Lights), a standard 120 VAC tungsten halogen lamp when operated at 122 VAC, increases its intensity to 106% of rated intensity while only attaining 77% of the rated life. Correspondingly, when the standard tungsten halogen lamp is operated at 128 VAC, the intensity increases to 125% of the rated intensity while the lamp life drops to 41% of its rated life. The discharge portion of the plot indicates that the lamp coming on drags down the load voltage by about 5 volts. Also, during discharge, any loads must be able to tolerate voltage swings from about 120 VAC to about 130 VAC.

Figure M-6 reveals the main battery charger current output to the battery bank during the charge cycle. The inverter current output to the load is shown for the discharge portion of the cycle. The average maximum current output is about 13 A while the average minimum current output by the inverter is about 5 A.

Figure M-7 indicates the wind speed during this charge/discharge cycle. Note that the sustained peaks occur at about a 24 hour interval. The cut-in wind speed for the HR2 wind generator is 8 mph. It can be seen from the plot that the wind energy input is not likely to be great since most of the time the wind speed is below the cut-in speed.

Figure M-8 is a plot of wind current generated by the wind turbine generator over the course of the charge/discharge. As anticipated from the previous plot, the wind current input occurs at those times when the wind speed appears to have had sustained operation above 8 mph.

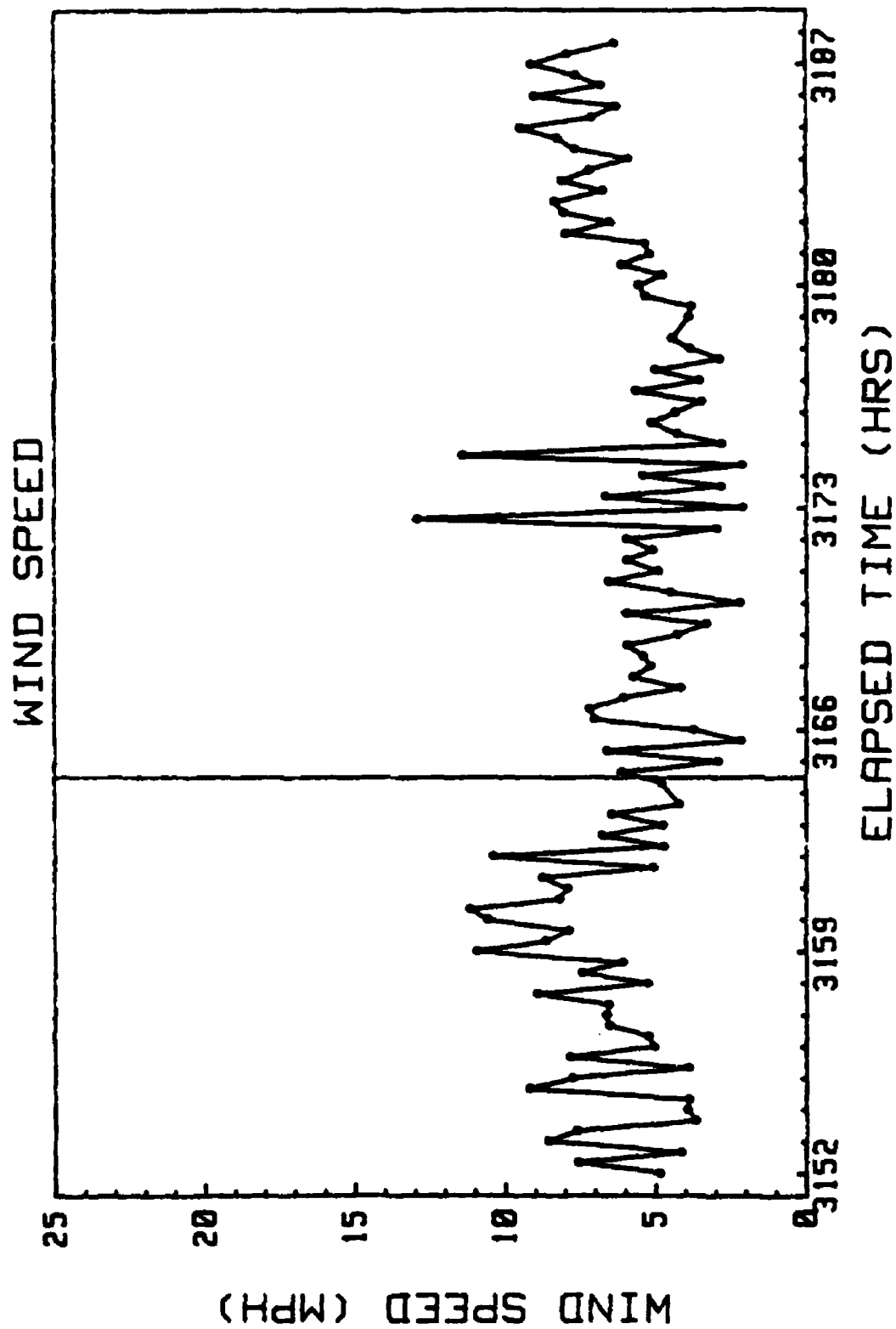


FIGURE M-7 WIND SPEED VS TIME

APPENDIX N ENVIRONMENTAL CONTROL UNIT

Purpose

Any energy management power system enclosure, whether on an existing lighthouse structure or on a portable fiberglass container, should have an environmental control unit installed for temperature and fresh air control. The environmental control unit consists of an air intake assembly, a vent assembly and a gravity damper.

Intake group

The intake assembly consists of a set of louvers which mix intake air from outside with the warm air from the inside of the volume. The mixing louvers are thermostatically controlled.

a. an electrically-driven fan motor mounted outside the intake mixing box pulls air through the louvers and forces the air through an inertial filter. The filter cleans the air of particles before the air enters the enclosure by forcing the air through many small vanes that make the air turn a sharp corner. The dirt in the air cannot make the sharp corner and collects at the end of the inertial filter as a dirty residue. The residue from the intake air is expelled from the filter through a dust collection chute to the exterior of the enclosure.

b. The outside air intake louvers are fully opened at room temperatures of 76°F and above and are essentially closed at 74°F and below. The inside air intake louvers are coupled to the outside air intake louvers in opposition so that one set is closed when the other is opened and vice versa. This keeps the air velocity constant through the inertial air filter.

Vent Group

The exit air vent assembly also contains thermostatically operated louvers. These louvers proportion the quantities of engine-heated air that are discharged out of and into the enclosure. At room temperatures of 74°F and above all heated air from the engine is discharged outside the volume; for room temperatures below 72°F, all heated air is discharged into the interior of the volume. Between these two temperatures some is discharged outside and some is discharged inside.

Initiation

The control motors can be powered-up as soon as AC power is available. The vent unit can be checked by adjusting its thermostat above room temperature. The Modutrol motor should open the inside vent allowing warm air from the engine cooling system to re-enter the building. Setting the thermostat below room temperature should cause the same louvers to close.

APPENDIX O SAFETY CONSIDERATIONS

There are numerous safety considerations for an energy management system. The general areas of concern may be categorized as: electrical, tower, and battery. These are summarized below.

Battery Safety

(1) The primary safety concern for a flooded, lead-acid, traction type battery is ventilation. During charging, both hydrogen (H_2) and oxygen (O_2) are evolved. These gases, when mixed in the appropriate concentration form a high explosive. The explosion danger is present whenever hydrogen gas is in the 4 to 76 percent by volume range (BIS, 1984). Exhausting the room volume once each minute is adequate. The amount of gas evolved depends heavily on the charge regime employed but typically, significant gassing can be expected to begin at about 75% to 80% SOC and continue after charging has ceased. The National Electric Code (article 480-9, 1984) requires the use of flame arrestors on vented lead-acid cells. These flame arrestors reduce the explosion hazard from gas mixture within the cell. Hydrogen, oxygen recombination caps also reduce the explosion danger (as well as providing beneficial water savings).

(2) In cells containing lead-antimony in the grid assembly, trace amounts of Stibine, SbH_3 , and Arsine, AsH_3 , both highly toxic (and potentially fatal) can be present during gassing. Sufficient ventilation eliminates this problem.

(3) Smoking or other open flames is not permitted in the battery enclosure at any time.

(4) The 120 V battery system is capable of rendering a lethal shock. The top of the battery should be covered. In our system, the cover consisted of 1/2 inch plastic or vinyl sheeting supported by a 2 in. X 4 in. frame. Preferably, the cover should be sectionalized to allow access to part of the battery bank at a time. The idea is to minimize exposure to the potentially lethal battery terminals. Although the frame should be sturdy, under no circumstances should this cover be used as a storage space or chair.

(5) It is not desirable to work over the batteries. Therefore, if possible, other equipment should not be located over the batteries.

(6) Access to battery enclosure should be strictly limited to authorized personnel. This is a high voltage, potentially lethal system. High Voltage signs should be posted.

(7) Splash-proof goggles, available through the federal stock system, rubber gloves and rubber apron should also be worn by servicing personnel.

(8) There should be eyewash stations within the battery enclosure as well as easy access to acid neutralizing solutions.

(7) CO₂ or HALON fire extinguishing systems should be employed in lieu of water. The system installed in this prototype is adequate.

(8) Noise suppressors (headgear) should be available for maintenance required when diesel generator is operating.

Wind Machine

(1) Page 4-55 of the United States Coast Guard Aids to Navigation Technical Manual indicates that a safety climbing device (ratcheting type) should be installed on tower structures taller than 20 ft. Such a device would provide little help for most of the maintenance work required because it limits maneuverability and access to various parts of the alternator. To do maintenance on the wind turbine generator, a nylon webbed safety harness should be worn. Personnel should be tied off to the top of the tower using nylon line equipped with locking carrabiners. Steel-toed working boots with a thick soles are recommended since the body weight will often rest on the angle iron tower structure.

(2) Before going aloft, the wind generator should be cranked to its feathered position using the wench located at the foot of the tower. The main storage batteries should also be disconnected.

(3) Personnel traffic at the base of the tower should be minimized while maintenance is being accomplished aloft. Ground personnel must wear hard hats while in the vicinity of the tower.

(4) Personnel should not be aloft in foul weather.

(5) Should the pullout chain (which furls the wind machine) break, personnel must wait until the wind subsides, then climb the tower and lash one of the blades to a tower leg. Once this has been accomplished, further maintenance may be pursued.

(6) As a general rule of thumb, the tower should be located at least the length of the tower plus one blade length away from any ground obstructions, such as buildings, in case the tower catastrophically fails.

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